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Quaternary Geologic History of the Coastal Plain of Rio Grande do Sul, Brazil

by

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QUATERNARY GEOLOGIC HISTORY

OF THE COASTAL PLAIN OF RIO GRANDE DO SUL, BRAZIL

by

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RESUMO

Este trabalho é um reconhecimento geológico preliminar da planície costeira do Rio Grande do Sul, Brasil. Os limites da planície costeira, temperatura, correntes maritimas, vento e direções do vento, regime de tempestades, marés e vazão da água nas embocaduras são discutidos. Os sedimentos mais jovens da planície costeira são divididos em Pleistoceno e Recente. Os sedimentos do Pleistoceno são subsequentemente divididos em saprolitos, arcózio e areias quartzíticas. Os sedimentos do Recente são separados em dois grupos gerais: areias quartzíticas a argilas ilíticas.

Uma classificação simples dos principais lagos e lagoas na área é oferecida. Perfís e estudos sedimentológicos da praia oceânica são também discutidos. Mapas generalizados batimétricos e de salinidade estão incluídos.

O histórico geológico da área é discutido e foram alcançadas as seguintes conclusões gerais:

(1) deposição de sedimentos do pré-Cambriano que foram posteriormente metamorfizados e granitizados;

(2) longo período de erosão;

(3) Deposição dos sedimentos e basaltos gondwânicos entre o Permiano e o Jurássico;

(4) Erosão e falhamento;

(5) deposição dos depósitos terciários;

(6) deposição e erosão parcial de sedimentos do Pleistoceno;

(7) falhamento;

(8) deposição de sedimentos do Recente;

Quanto a geologia quaternária, as três mais importantes conclusões alcançadas são:

(1) mudanças eustáticas ao nível do mar produziram um "drowned river mouth coast" no Rio Grande do Sul, no fim do Pleistoceno;

(2) grande restinga na costa do Rio Grande do Sul foi elevada por falhamento posterior ao Pleistoceno, a qual foi fundamental na gênesis da Lagoa dos Patos;

ABSTRACT

This paper is a preliminary geologic and geographic reconnaissance of the Coastal Plain of Rio Grande do Sul, Brazil. The coastal plain consists of 47,100 square kilometers, or 18,200 square miles, of low flat land bordered by higher land which is composed of rocks ranging in age from pre-Cambrian to Jurassic.

The intensity and direction of the wind is considered to be the most important physical process operating in the coastal plain. Eolian features are aligned parallel to the path of the prevailing northeast wind. The most important water bodies within the coastal plain are: (1) fault controlled lagoons, (2) fault controlled lakes, (3) larger lakes related to the topography of older rocks, (4) cordiform (heart-shaped) lakes, and (5) inlets. The two major ocean currents which operate along the coast of Rio Grande do Sul are the north-flowing (cold) Falkland (Malvinas) current, and the south-flowing (warm) Brazil current. Each carries a distinctive fauna.

Both Pleistocene and Recent sediments are recognized in the coastal plain. Pleistocene sediments are described as saprolites, arkoses, and quartzose sands. Recent sediments are separated into two groups, quartz sands and illitic clays.

The general geologic history of the area began with the deposition of pre-Cambrian sediments which were later metamorphosed and granitized. This was followed by a long period of erosion. Later, deposition of thick Permian to Jurassic Gondwana sediments and basalt was subsequently followed by post-Gondwana erosion and faulting. This faulting initiated a new basin where Tertiary sedimentary rocks were deposited. The continuous deposition of lower Pleistocene was followed by faulting and later deposition of Recent sediments.

In terms of Quaternary geology the three most important conclusions reached are: (1) eustatic changes in sea level produced a drowned river mouth coast in Rio Grande do Sul at the end of the Pleistocene, (2) the large sand bar on the coast of Rio Grande do Sul was uplifted by post-Pleistocene faulting which was fundamental to the genesis of the Lagôa dos Patos, and (3) the most important geologic process in operation today within the area studied is the force and direction of the wind.

In this paper it is concluded that:

(1) The Coastal Plain of Rio Grande do Sul is larger, and has a much greater complexity than was previously estimated.

(2) During the last Pleistocene glacial stage the coastal plain was probably a low lying, semi-arid, cold steppe trenched by streams whose valleys were generally oriented in an east-southeast direction.

(3) At the end of Pleistocene time the general aspect of Rio Grande do Sul must have been that of a crowned estuarine coast with narrow ocean beaches and perhaps a few islands offshore.

(4) Faulting has played an important part in determining Recent and Pleistocene morphology and was fundamental in initiating the barrier island complex of Southern Brazil.

(5) The Lagôa dos Patos apparently was structurally initiated by trapping of waters within a trough resulting from landward tilting of a fault block.

(6) The Triassic Botucatú sandstone is the principal source of coastal plain sand; however, there has been considerable mixing of this sand, thus indicating a second, at present unknown, source area.

(7) Aeolian transportation and deposition of sediment is a most important morphologic process since this action: (a) forms large dune fields and elongate sand tongues along the coast, (b) modifies the shapes of water bodies in the coastal plain, and (c) deposits a thin overlapping layer of Recent sand upon the older rocks bordering the coastal plain.

(8) The principal wind direction in the coastal plain is from the northeast, hence wind initiated or modified landforms have this orientation.

(9) The south-flowing Brazil current is dominant along the Rio Grande do Sul coast during summer (December thru February) and the north-flowing Falkland current is important during winter (June thru August). Both ocean currents are significant in terms of sediment distribution; however, prevailing littoral drift is southerly.

(10) Endemic plants and animals are antiboreal, others are transported by ocean currents.

(11) The flora of the Rio Grande do Sul Coastal Plain is different from that of northern Brazilian coasts in that mangrove and coastal forests generally are absent.

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INTRODUCTION

Rio Grande do Sul, the southernmost state of Brazil, is one of the largest and most incompletely known parts of South America. Eckman (1952) recently stated, "... the region between Patagonia and Rio de Janeiro is one of the worlds least known regions as far as coastal fauna is concerned." A similar statement would be appropriate in the fields of physical geography and geology.

Recently an opportunity arose through the Coastal Studies Institute of Louisiana State University which enabled the writer to spend a year studying the coastal part of this area. The purpose of this study was to make a general reconnaissance of the coastal plain of Rio Grande do Sul (Fig. 1); a region covering an area of 47,150 square kilometers or 18,200 square miles. Vast size of the area, inaccessibility, and abnormally heavy rains and floods precluded investigation of the southern extremities of the coastal plain. Therefore, emphasis in this report is placed on the northern and central portions of Rio Grande do Sul, or on the area between 29° 20' and 31° 10' South Latitude and 50° 15' and 51° 15' West Longitude (Figs. 2, 3 and 4).

Field work was begun in the northern part of the area during the southern hemisphere spring of 1958. Later, during the summer, field work was carried on intensively in the area of Rio Grande. Additional field work was done during vacations and holidays throughout the academic year. Dr. James P. Morgan accompanied the writer in the field during the months of July and August.

The writer wishes to acknowledge assistance of the Geography Branch, Office of Naval Research, and the Coastal Studies Institute, for their complete cooperation with this project. Furthermore, the writer wishes to thank Dr. James P. Morgan, Managing Director of the Coastal Studies Institute, for his understanding, guidance, and interest in this project. Thanks are also due to various Brazilian Institutes, namely, the Escola de Geologia, Universidade do Rio Grande do Sul, the Marinha do Brazil and the Departamento de Rios, Pôrtos e Canais. In particular, the author wishes to thank Eng. F. Duprat and Eng. Cícero Vassao of the Escola de Engenharia Industrial de Rio Grande; Sr. Boaventura Barcelos of the museu de Estudos Oceanográficos do Rio Grande; Luiz Martins, Paulo Miranda de Figueiredo Filho, Maurício Ribeior, Luís Eduardo Neves, Carlos Beltrami, Jose Gabriel de Cunha e Souze Filho, Darcy Closs Enio Medeiros Ramos, and Sílvio Zembruski, of the Escola de Geologia da Universidade do Rio Grande do Sul, for their individual cooperation.

DESCRIPTION OF AREA

Rio Grande do Sul, the southernmost state of Brazil, borders

Fig. 1. Index map of Brazil and Rio Grande do Sul.

Uruguay on the south, the state of Santa Catarina on the north, and Argentina on the west (Fig. 1). The total area of the state is 282,480 square kilometers (109,036 square miles, or about the size of the state of Nevada), of this approximately 47,150 square kilometers, or 17 percent of the state, lies within the coastal plain. The coastline of Rio Grande do Sul is 620 kilometers (388 miles) long. It extends from Chuí in the south to the mouth of the Mampituba River in the north.

This area is considerably larger than the coastal plain of other states in Brazil south of the bulge. From 10° South Latitude, the coast is principally rocky and is composed of ancient gneissic and granitic bed rock with a narrow strip of quartz sand beaches. The entire coast from Salvador da Bahia south to Florianópolis, Santa Catarina, is rocky. It was submerged not long ago but has recently emerged. South of Florianópolis, "pocket" sand beaches 2 to 50 kilometers (approximately 1 to 31 miles) from headland to headland are a common feature. Further south in Rio Grande do Sul one of the worlds longest uninterrupted sand beaches extends from the coastal town of Tôrres (Fig. 2) south to Uruguay. This beach is at least 640 kilometers (400 miles) long and has a maximum width of 100 kilometers (62 miles).

In certain respects the Coastal Plain of Rio Grande do Sul is similar to the northwest Gulf Coastal Plain of Texas and the Carolina Coastal Plain of the eastern United States. The similarities are: (1) all have barrier islands with bays, sounds or lagoons landward, (2) the edge of the coastal plain is irregular and scalloped, (3) lithologically they are arenaceous, (4) all have Pleistocene and Recent sediments overlying marine Tertiary sediments, and (5) they have generally similar latitudes and climates.

Although the similarities are striking, the Rio Grande do Sul coastal plain is somewhat different from the other two areas because: (1) the barrier is much larger, longer, and has only one inlet, (2) the sounds are much larger, (3) the dominant wind directions are more constant, and (4) two ocean currents operate along the coast during differing seasons of the year.

Topographically the Rio Grande do Sul Coastal Plain consists of a flat lowland whose elevations are seldom more than 6 meters, or 20 feet. Exceptions to this occur where the crests of sand dunes may range as high as 20 meters, or 65 feet, and isolated basalt remnants at Tôrres as high as 66 meters, or 217 feet (Fig. 5 and 6).

In contrast to the low, flat coastal plain the bordering highlands rise rather abruptly (Fig. 7) to elevations of more than 1,000 meters, or 3,300 feet, in the north and more than 400 meters, or 1,300 feet, in the south.

Politically the State of Rio Grande do Sul is subdivided into municipalities. This subdivision is very common in Brazil and is roughly equivalent to counties in the United States. The term "municipality" stems from historic times when Rio Grande do Sul was known as the Province of São Pedro. Each municipality has a "sede", county seat, which is normally its most important town. More im-

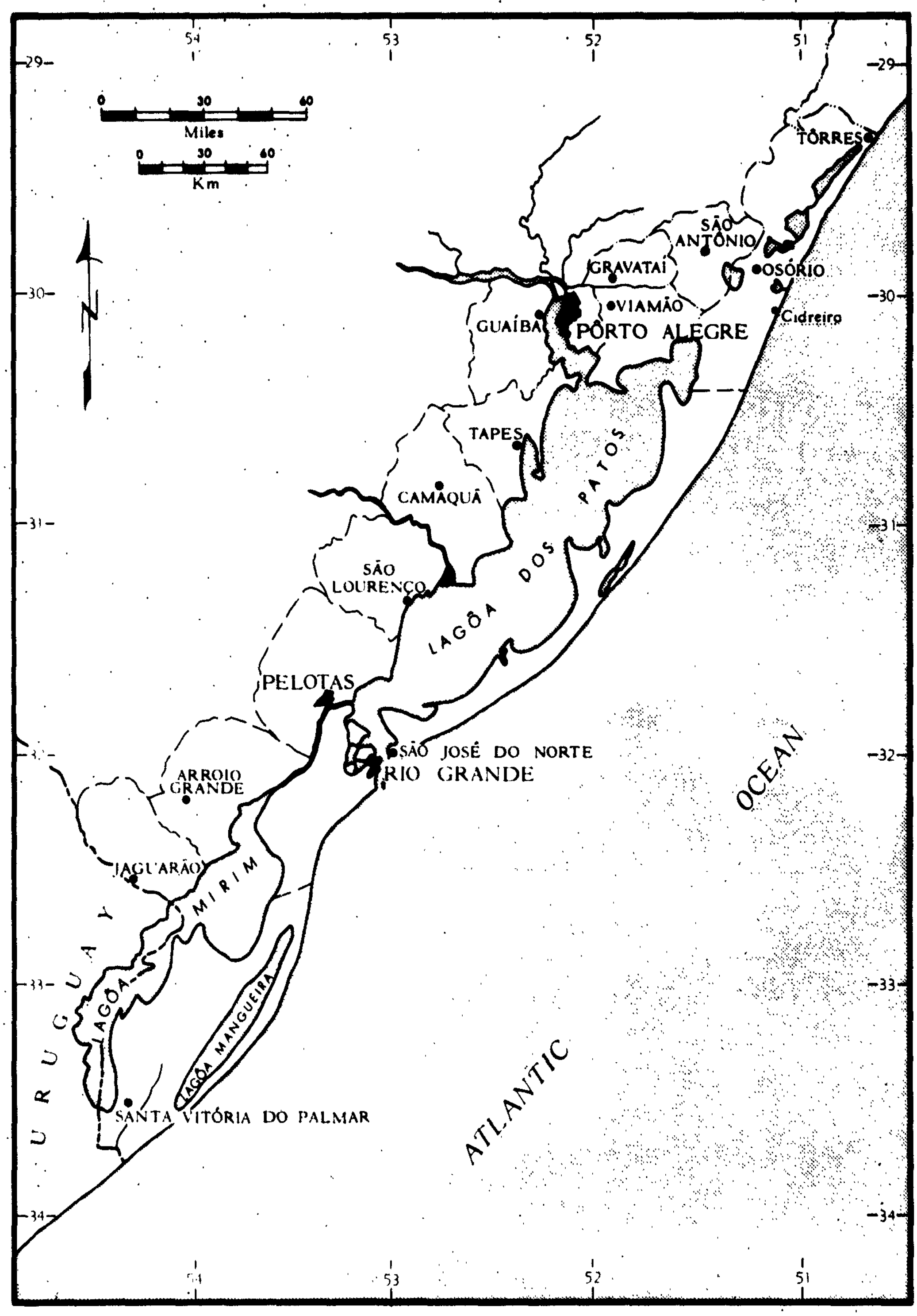


Fig. 2. Political map of the Coastal Plain of Rio Grande do Sul.

portant municipalities in the coastal plain are Tôrres, Osório, São José do Norte, Rio Grande, Santa Vitória do Palmar, Jaguarão, Arroio Grande, Pelotas, São Lourenco do Sul, Camaquã, Tapes, Guaíba, Pôrto Alegre, and Viamão (Fig. 2).

Although the coastal plain of Rio Grande do Sul is a large area, it is definitely underpopulated. This is particularly true in the municipalities of São José do Norte and Santa Vitória do Palmar, which have population densities of only four to six people per square kilometer, whereas the state average is seventeen and eight-tenths people per square kilometer. Population statistics are somewhat misleading within the coastal plain, as in every other area in Rio Grande do Sul, because population densities tend to be concentrated in the "sedes" of the municipalities due to landowners preferring to live in the city rather than on the land. Table 1 shows this relationship:

TABLE 1

Population and Area of Coastal Plain Municipalities

Municipalities	"Sede" Pop.	Total Pop.	Area (Sq. Km.)
Arrôio Grande	3,890	19,890	3,002
Camaquã	3,750	37,850	2,712
Guaíba	5,060	25,720	1,912
Osório	4,190	49,600	2,609
Pôrto Alegre	461,440	484,790	482
Rio Grande	71,740	88,110	2,617
Sta. Vitória do Palmar	6,620	16,570	4,774
São José do Norte	2,060	24,760	3,934
São Lourenço do Sul	5,350	35,530	2,299
Tapes	3,500	25,270	1,796
Tôrres	4,040	34,880	971

There are three all-weather roads which extend from Pôrto Alegre to the Atlantic Ocean. They connect Pôrto Alegre and Tôrres, BR-RS-59; Pôrto Alegre and Tramandaí, BR-RS-14; and Pôrto Alegre-Pelotas and Rio Grande, BR-2, BR-77.

Table 2 lists and describes the principal roads, and Table 3, the secondary roads of the area. In addition to these, another natural roadway exists along the Atlantic shore which may be traversed when the ocean is calm and the winds are from the northeast. This beach road, called "Estrada da Praia," lies at the water's edge where the sand has been compacted and wetted by the waves (Table 4). Traffic along the beach is precarious during most of the year.

TABLE 2

Principal Roads of the Coastal Plain

Name of Road and Type	Length (Kms.)	Length (Miles)	Kms South fr. Mampituba R.
Mampituba-Torres, Graded Dirt	7	4.3	Torres 7
Tôrres-Pte. Maquiné, Gravel	70	43.4	77
Pte. Maquiné-Osório, Gravel	32	19.9	109
Osório-Tramandaí, Asphalt	22	13.6	131
Osório-Sta. Antônio, Asphalt	30	18.6	255
Sta. Antônio-Gravataí, Asphalt	34	21.1	195
Gravataí-Cachoeirinha, Asphalt	14	8.7	209
Cachoeirinha-P. Alegre, Asphalt	16	9.9	225
P. Alegre-Guaíba, Asphalt	30	18.6	255
Guaíba-Camaquã, Asphalt	96	59.4	351
Camaquã-Boqueirão, Graded Dirt	39	24.1	390
Boqueirão-Pelotas, Graded Dirt	80	49.1	470
Pelotas-Quinta, Asphalt	36	22.1	506

TABLE 3

Secondary Roads of the Coastal Plain

Name of Road and Type	Length (Kms.)	Length (Miles)
P. Alegre-Viamão, Asphalt	23	14.3
Viamão-Palmares, Gravel	70	43.4
Viamão-Pinhal, Dirt	88	54.6
P. Alegre-Belém Novo, Asphalt	28	17.4
Belém Novo-Itapoã, Gravel	22	13.7
Itapoã-Leprosário, Gravel	9	5.6

TABLE 4

Beach Distances and Settlements along the "Estrada da Praia"
Tôrres to Sao José do Norte

Name of Road	Length (Kms.)	Length (Miles)	Percent of year passable with Automobile (est.)
Torres-Praia do Cal	2	1.2	100
Praia do Cal-Itapeva	5	3.1	90
Itapeva-Gaúcha-Recrêio-Santa Helena	5	3.1	80
Santa Helena-Rondinha	10	6.2	80
Rondinha-Arrôio do Sal	8	5	70
Arrôio do Sal-Bom Jesus-Curumim-Arrôio Teixeira	12	7.5	70
Arrôio Teixeira-Capão da Canôa	14	8.7	60
Capão da Canôa-Atlântida-Ibagé	10	6.2	95
Ibagé-Santa Terezinha	7	4.3	80
Santa Terezinha-Imbé	10	6.2	70
Imbé-Tramandaí	2	1.2	100
Tramandaí-Oasis	8	5	90
Oasis-Barro Prêto-Cidreira	14	8.7	70
Cidreira-Pinhal	8	5	60
Pinhal-Palmares	43	26.7	35
Palmares-Pangaré	39	24.2	25
Pangaré-Lagoa da Reserva-Mostardas	76	47.3	25
Mostardas-Tavares	27	16.8	20
Tavares-Lagoa do Bojurú	46	28.6	20
Bojurú-Estreito-São José do Norte	83	51.6	20

LIMITS OF THE COASTAL PLAIN

The Rio Grande do Sul Coastal Plain is a low sand plain which has as its eastern limit the Atlantic Ocean, and as its western limit an arcuate belt of higher land. The latter forms a natural physiographic boundary where resistant crystalline rocks form steeper slopes or sharp scarps that rise above the adjacent low sand plain (Fig. 7). Rocks comprising the highlands range in age from pre-Cambrian to Jurassic. Generally, the pre-Cambrian rocks are acidic igneous and metaphorphics, upper Paleozoic rocks are siltstones, Triassic rocks are eolian sandstones, and Jurassic rocks are extrusive basalt lavas.

Acidic igneous and metamorphic rocks crop out in an arcuate belt from the Coxilha dos Lombos (Fig. 3) south to Itapoã, then west across

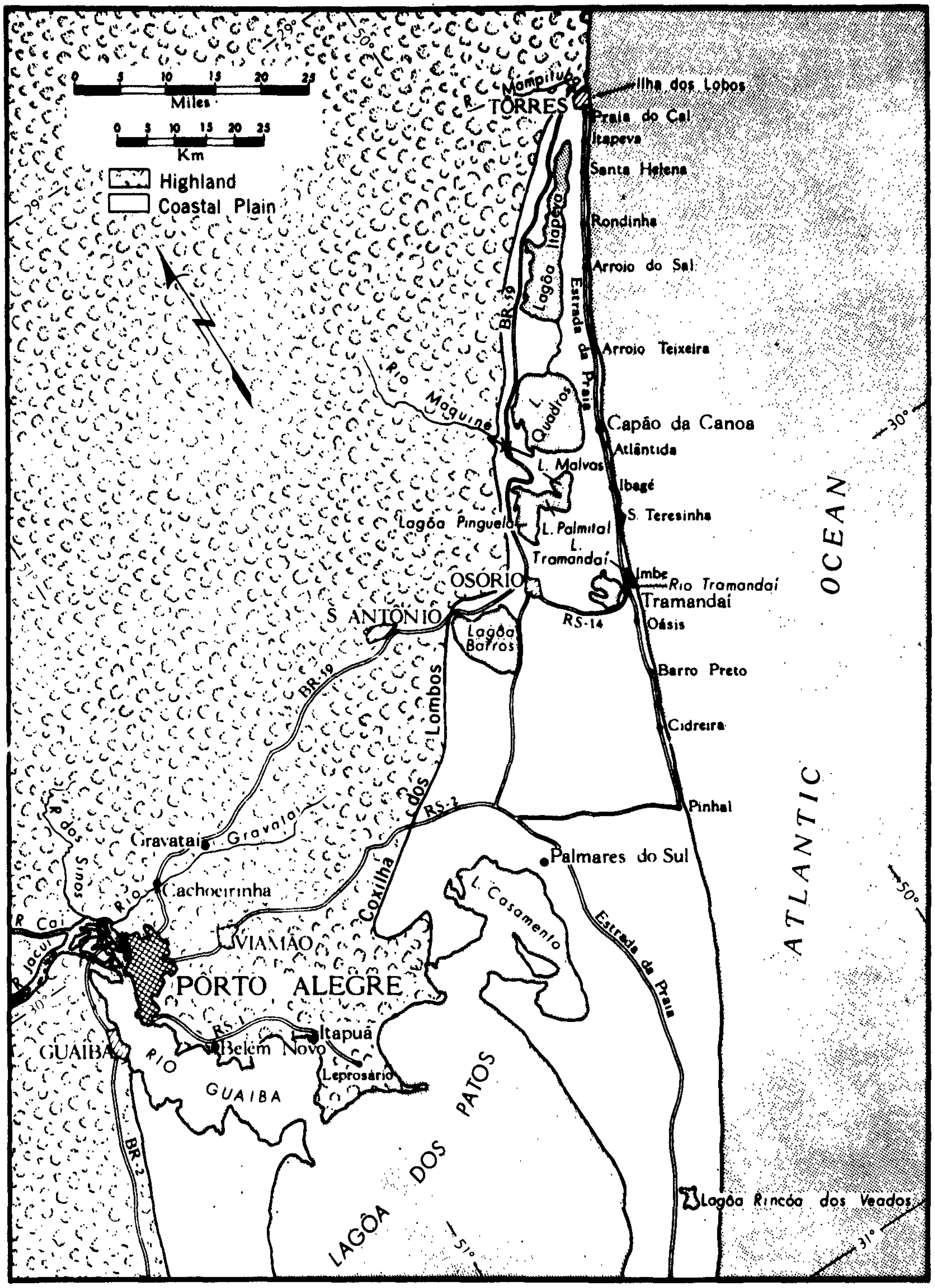


Fig. 3. Index map of the northern portion of the Coastal Plain, Brazil.

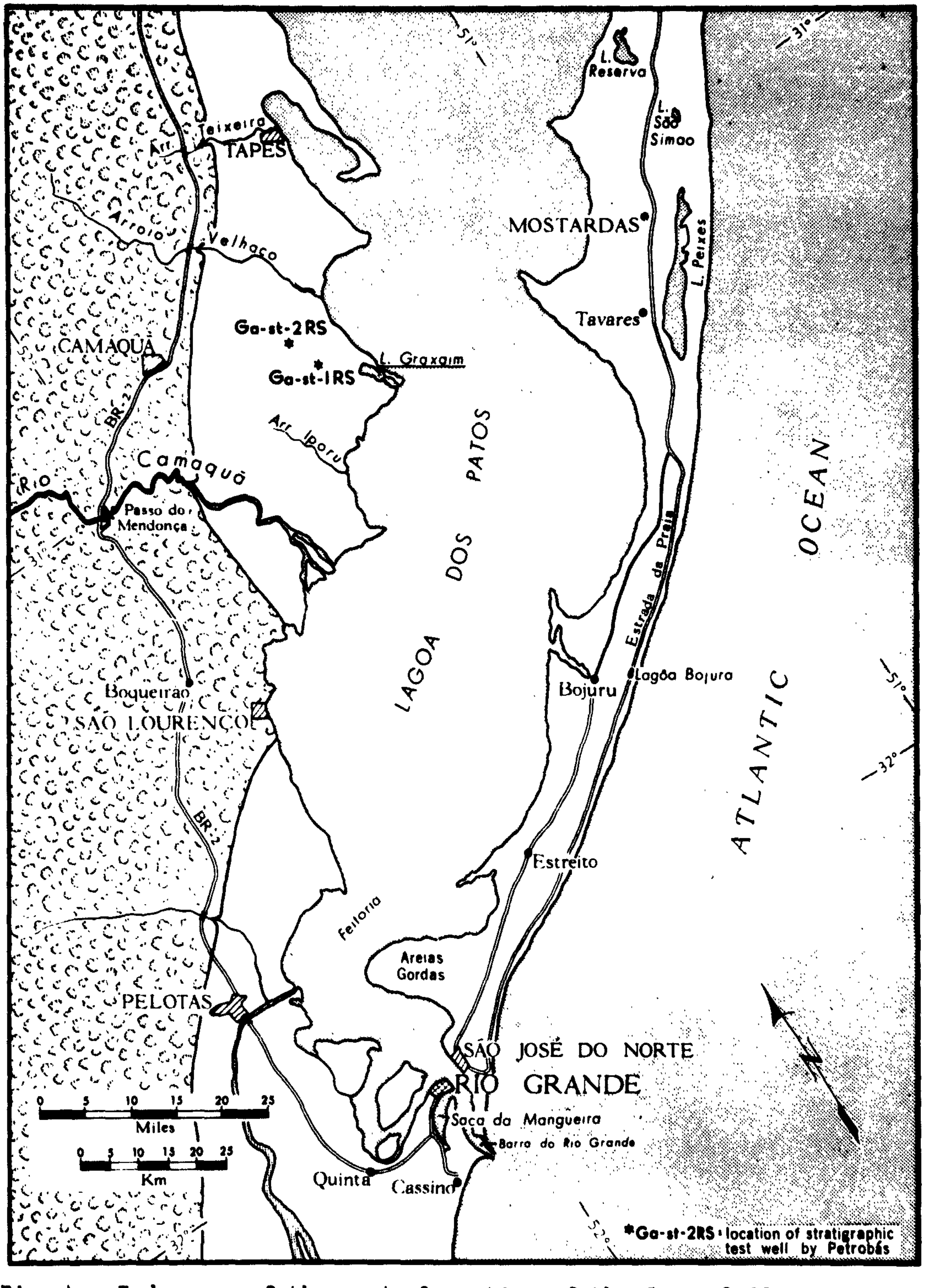


Fig. 4. Index map of the central portion of the Coastal Plain, Brazil.

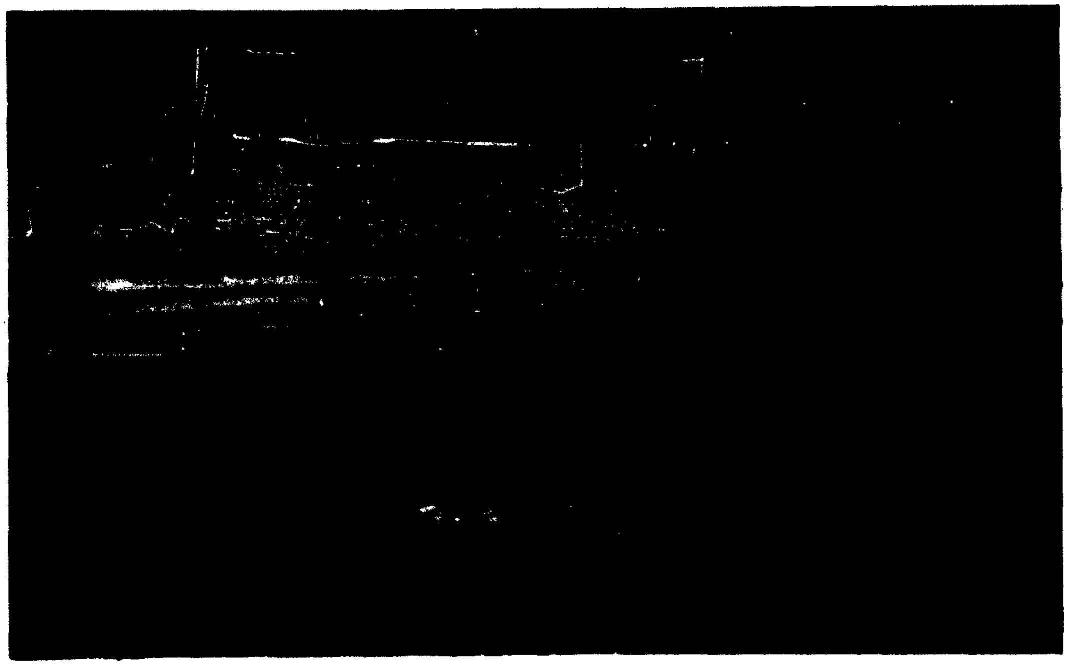


Fig. 5. Basalt remnants at Torres.

Fig. 6. Praia da Guarita, showing the contact between the Botucatú sandstone and the Serra Geral basalt.

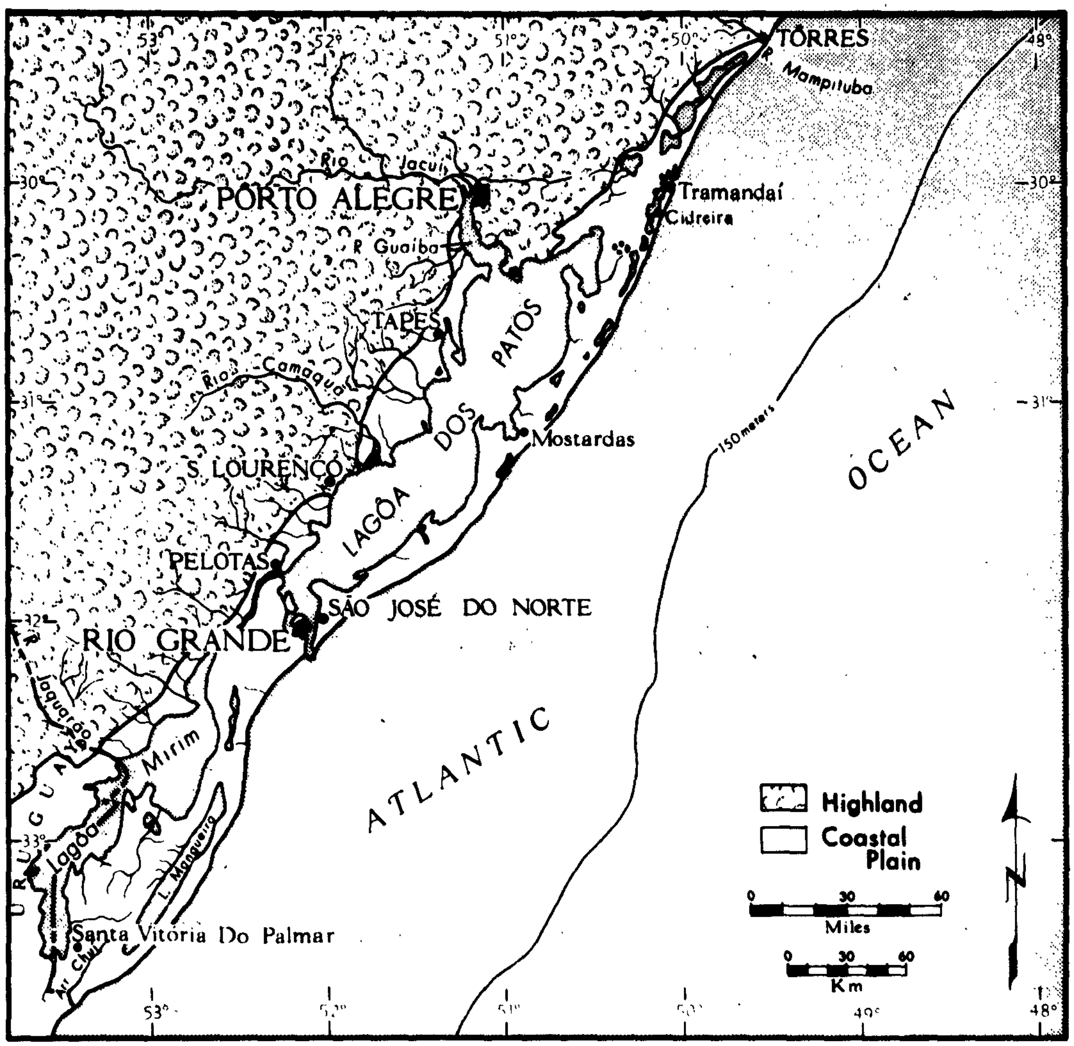


Fig. 7. Map showing the relationship of highlands, lowlands and edge of the continental shelf along the coast of Rio Grande do Sul.

the Guaíba estuary as small islands to the Serra de Tapes (Fig. 4) where they attain elevations of 100 to 400 meters (320 to 1,300 feet) or more. São Lourenço do Sul is the only locality on the Lagôa dos Patos south of the mouth of the Guaíba River where these rocks are exposed (Fig. 9). South of São Lourenço granitic and metamorphic rocks crop out in an arcuate band which passes west of Pelotas and extends south into Uruguay. The granitic rocks have not been given a formal name. The metamorphic rocks are grouped in the Porongos Series and are considered to be of upper pre-Cambrian age.

Upper Paleozoic rocks are not particularly extensive in the coastal plain as they are exposed only in the area west of the Coxilha dos Lombos (Fig. 3). These rocks are normally considered to be equivalent to the Rio Pardo formation and have been assigned to the upper Permian (Delaney and Goñi, 1961). Lithologically the Rio Pardo consists of red and whitish sandstones and siltstones.

Triassic rocks are significant in the Coastal Plain of Rio Grande do Sul where they form exposures in the southern, western, and northwestern portions of the Lagôa dos Barros, and in an arcuate strip from the western margin of the Lagôa Itapeva to the Atlantic Ocean at Tôrres (Fig. 3). These sediments consist of red to pink eolian sandstones known as the Botucatú formation.

Jurassic rocks are exclusively basaltic lavas and occur on the surface from the northern margin of the Lagôa dos Barros to Tôrres (Fig. 3). Several outliers of basalt occur at Itapeva (Fig. 5) and form the Ilha dos Lôbos some 2 kilometers offshore from Tôrres. Lithologies, stratigraphic position, and geologic history of these basalts, which have been named the Serra Geral formation, are discussed more fully in a later section.

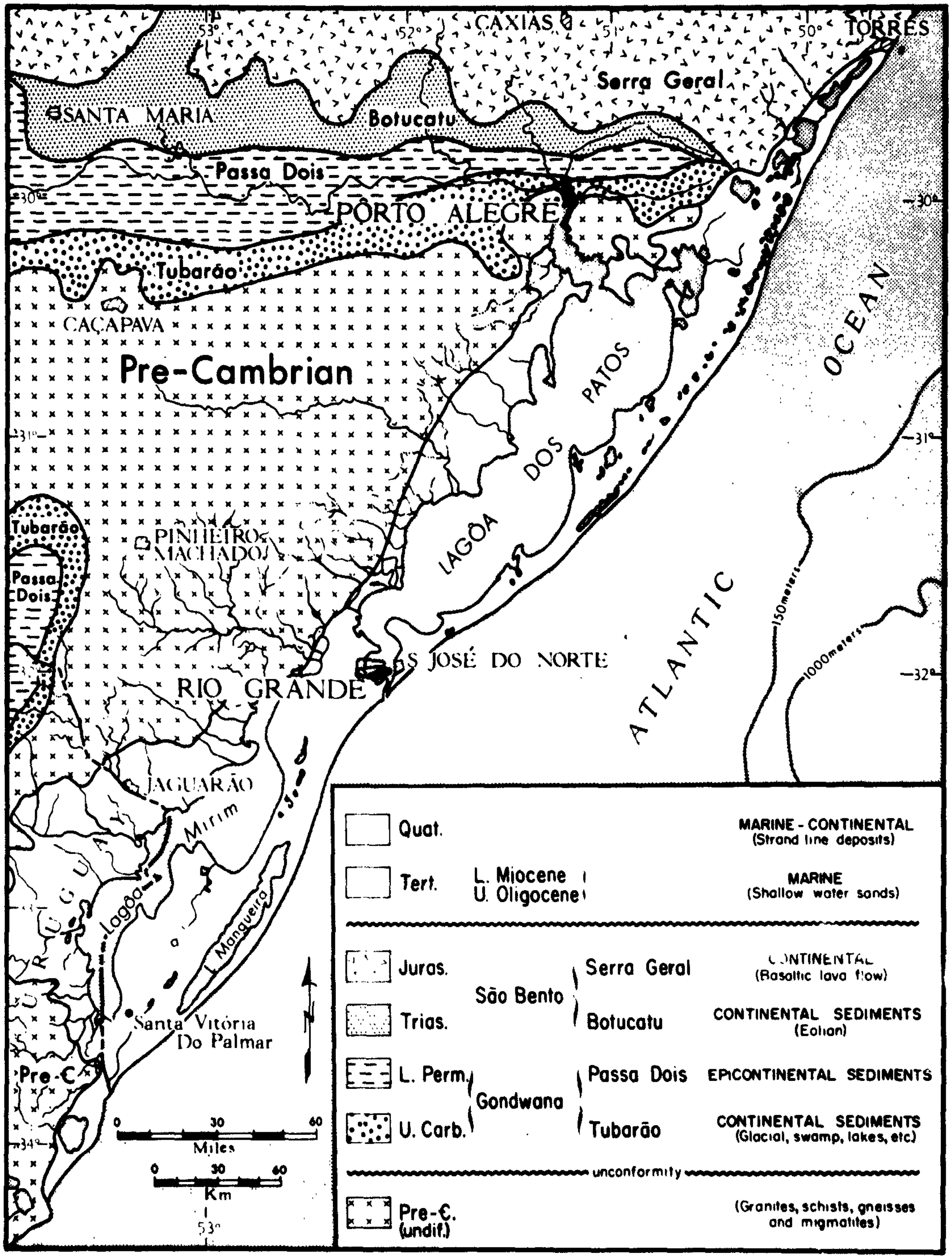


Fig. 8. Geologic sketch map of the area with the Mostardas fault zone shown.

PHYSICAL ELEMENTS

In describing the Rio Grande do Sul Coastal Plain it is necessary to include a brief discussion of the important physical processes and agents active within the area before more complex matters such as geologic patterns, processes, and associations are considered. Physical agents of significance within this area are: climate, dynamics of interior water bodies, nearshore hydrography, currents, waves and tides, and stream discharge.

CLIMATE

In general the coastal plain climate can be described as humid, warm, and rainy. The annual average temperature is 17.5° Centigrade (63.5° Fahrenheit). Rainfall is normally 1300 millimeters (50 inches) per year (Machado, 1950). There are between 92 and 110 rainy days per year. Frost has rarely been known to occur in the area.

Machado (1950) has divided the coastal plain into two subclimatic areas, "Litoral Norte" and "Litoral Sul." He has based this subdivision on the fact that the northern part of the area does not feel the effects of the cold winter winds because it is protected by the basalt escarpment. Furthermore, he states that the southern part of the coastal plain is completely unsheltered from thermal action of the ocean. It is felt that this climatic subdivision is interesting, but does not have any morphological significance, at least in the light of present knowledge.

Air temperature within the coastal plain is quite variable. The annual mean temperature is 17.5° C. (63.5° F.) in the south, and 17.9° C. (64.2° F.) in the north. The absolute maxima are 42° C. (107° F.) in the south, and 36° C. (96.8° F.) in the north. The extreme absolute values are 42.6° C. (108.6° F.) and -5.2° C. (+22.7° F.), (Machado, 1950).

Water temperature of rivers in the coastal plain is quite variable. Unpublished data collected during the last five years by the Departamento Estadual de Pôrtos, Rios e Canais, shows that the Tramandaí River (Fig. 3) has its lowest temperature during the months of June and July (12.4° to 15.3° C., or 54.3° to 59.5° F.), while highest temperatures were recorded during January and February (26.0° C. to 27.2° C., or 78.8° to 81.0° F.). Other water bodies in the area tend to follow this general pattern.

Ocean temperatures vary with the season of the year, ocean current in operation, and depth. Data are very scarce; however, temperature measurements made by the Marinha do Brasil during April 1958 indicate that the nearshore surface water (up to 100 meters in depth) has a mean temperature of 20° C. (68° F.). Temperature data collected

by fishing vessels during the months of October and November 1958 indicates that the surface water in the southern part of the area has a temperature of approximately 15° C. (59° F.).

Since the coast of Rio Grande do Sul is greatly influenced by eolian processes, wind intensity and direction are fundamental to an understanding of the geomorphic landscape. Prevailing winds in the coastal plain come from the northeast. They probably result from the large tropical and sub-tropical high pressure area prevalent in the Atlantic Ocean near 30° South Latitude. Thus, the winds at the coastal station of Tôrres (Fig. 2) have been dominantly from the northeast, since the first records of wind directions were taken in 1913 (Machado, 1950). Besides this prevailing wind, there are two other accessory winds which have been given names by the local residents - the "Minuano" and the "Carpinteiro da Costa."

The Minuano is a cold, dry, continental, west wind which is caused by invasion of Polar Pacific air masses into Rio Grande do Sul. The Minuano derives its name from an ancient tribe of Indians who lived west of the coastal plain. The "Carpinteiro da Costa" is a southeast or south-southeast wind, and is related to the resistance of the Polar Atlantic air mass against the Tropical Atlantic air mass. It is an on-shore, oceanic wind, and normally blows for three or four days at a time. It has received its name, "Carpenter of the Coast," because when it blows, traffic along the beach, as well as coastal navigation, is hazardous as a result of large quantities of displaced sand. Many navigation accidents occur when this wind blows because quantities of bottom sand are shifted further out on the continental shelf, changing configuration of shoals or banks, and the force of the wind from the southeast causes the ships to drift inshore. During this study three ships ran aground - two near Pinhal (Fig. 3), and the other crashed into the Ilha dos Lôbos (Fig. 3). Normally, when a ship runs aground it is not salvaged because the ocean bottom is too shallow to allow tug boats to approach the stranded vessel, therefore it is abandoned. (Fig. 10).

Figures 11 and 12 are diagrammatic "wind roses" for Tôrres, Imbé, Tapes, Mostardas, Pelotas, Rio Grande, Jaguarão, and Santa Vitório for the period 1952 through 1956. Figure 11 includes the five year annual averages while Figure 12 shows the five year seasonal averages. Because they deviate from conventional wind roses it is necessary to describe briefly the method of construction. The length of each wind vector is based on the frequency of wind observations made by an observer thrice daily (7 AM, 2 PM, and 9 PM) at each station over a five year period. Each centimeter is equal to twenty observations. Thus, if an observer noted that during the month of March at the forestated times the wind was blowing 49 times from the northeast, 16 times from the east, 9 times from the south, 9 times from the west and for 10 observations there was no wind; the corresponding vectors would have as their length: NE 2.45 cm., E .8 cm., S .45 cm., and W .45 cm. This method differs slightly from the usual percent-time method of wind rose construction. Utilization of this slightly more complicated method was necessitated by the lack of night wind observations. Each feather on the wind rose has a value of five kilometers per hour (or 3 miles per hour). In some cases it was not possible to put the appropriate number of feathers

Fig. 9. Granitic rocks cropping out at São Lourenço.

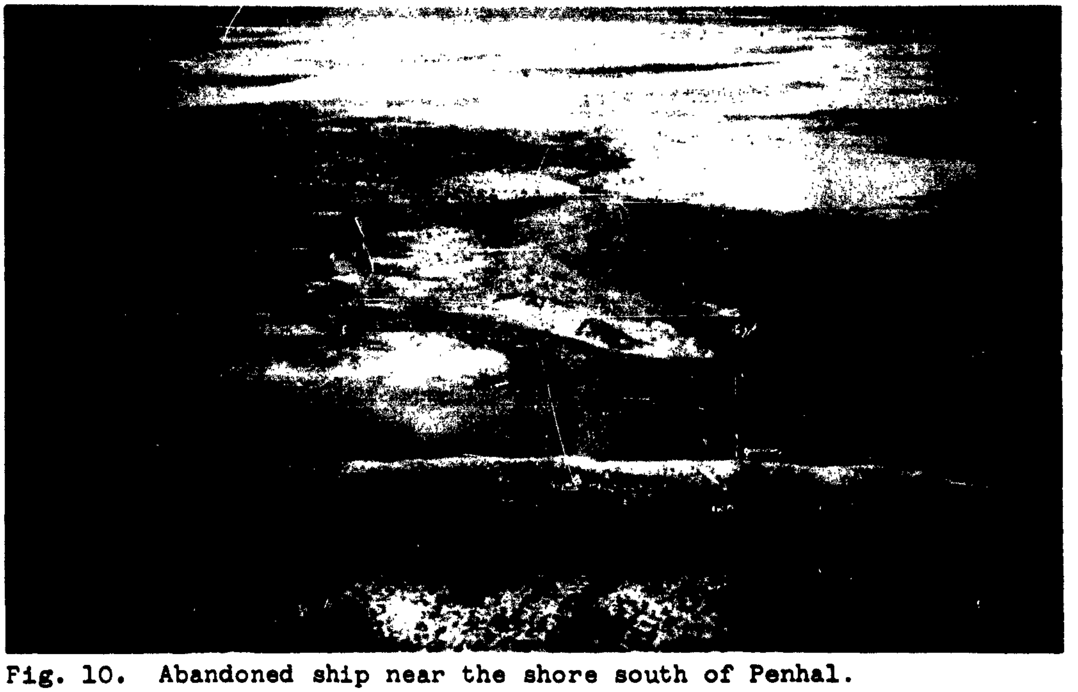


Fig. 10. Abandoned ship near the shore south of Penhal.

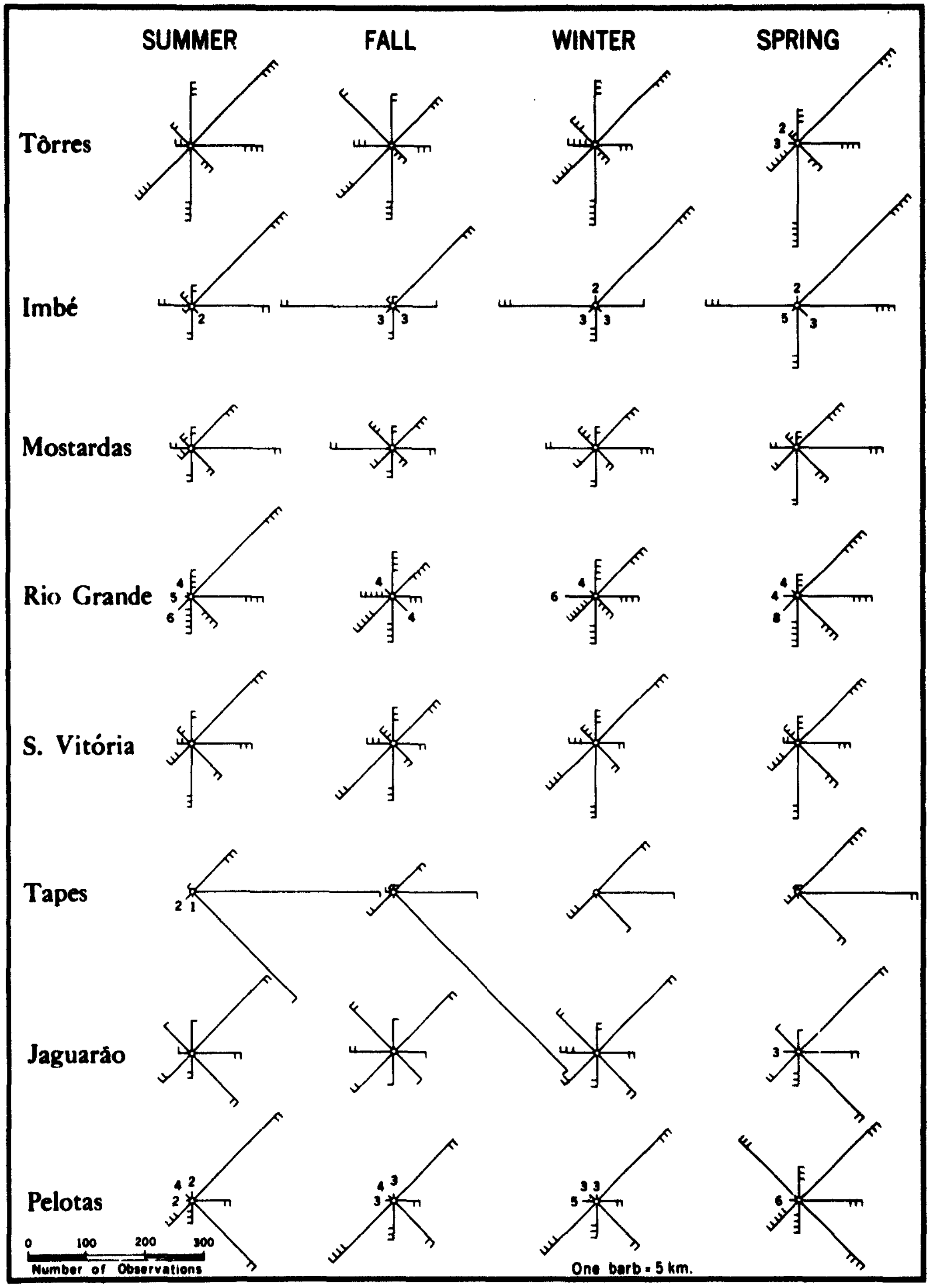


Fig. 11. Seasonal wind roses.

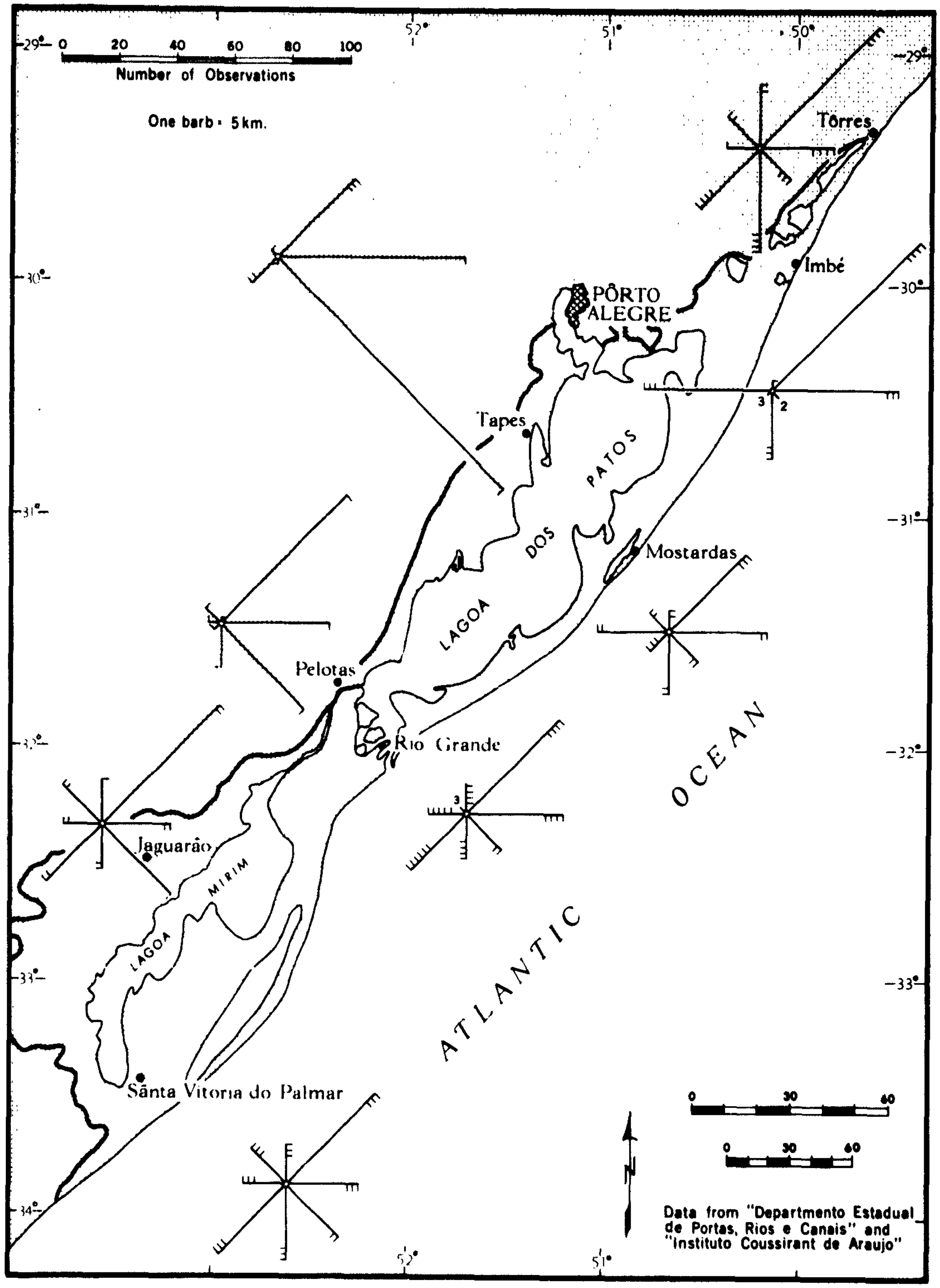


Fig. 12. Wind roses along the coast of Rio Grande do Sul (5 year average).

on certain vectors because the vector was too short. In such cases the value is given by a figure located next to the vector.

From Figures 11 and 12 we may conclude that: 1) during all seasons of the year the northeast wind is dominant, 2) during fall and winter months the Minuano is more important than during spring and summer, 3) during winter months the Carpinteiro da Costa is most important, and 4) during all seasons of the year the prevailing wind directions are northeast, east, southeast, south, and west.

WATER BODIES

Hydrographically, Rio Grande do Sul is subdivisible into two distinct basins. The first consists of the Uruguay River drainage basin which eventually empties into the estuary of the Rio de la Plata, and secondly, the lacustrian system which drains directly into the Atlantic Ocean. The latter predominates in the eastern portion of the state and is of primary importance within the coastal plain. This system is considered lacustrian because almost all precipitation within the basin passes through an intermediate lake or lagoon before entering the Atlantic Ocean.

Major streams of eastern Rio Grande do Sul consist of the Camaquã and Jaguarão Rivers, which discharge centrally into the Lagôa dos Patos and the Lagôa Mirim respectively; the Tramandaí River, Mampituba River and the Arrôjo Chui, which discharge into the Atlantic Ocean, and the Guaíba River on which is situated Pôrto Alegre (Fig.7). The Guaíba is a broad estuarine valley into the head of which discharge the Jacuí, Sinos, Gravataí, and Caí rivers (Fig. 3).

There are many lakes and lagoons in the area, the largest being the Lagôa dos Patos and the Lagôa Mirim. These water bodies together occupy an area of 13,680 square kilometers (5,280 square miles), a size comparable with Lake Maracaibo in Venezuela, or slightly smaller than Lake Ontario in North America.

The Lagôa dos Patos (9,910 square kilometers, or 3,825 square miles) is more than one and one-half times as large as the Great Salt Lake in the United States. The Lagôa Mirim (3,770 square kilometers or 1,455 square miles) is more than twice as large as Lake Pontchartrain in Louisiana. The following table lists the ten most important lakes in the Coastal Plain of Rio Grande do Sul, their respective areas, and approximate maximum depths. The numbers in parentheses are local deep spots or scour holes.

Generally, water depth is proportional to lake size. The Lagôa dos Patos, near the middle of the lake, is only 8.7 meters or 28.5 feet deep. There are certain exceptions to this, however, such as a scour hole near Itapoã (Fig. 3) where the bottom is 40 meters or 131 feet deep.

TABLE 5

Larger Lakes of the Coastal Plain

	Name	Area Km²	Area Mi²	Mamimum Depths Meters	Mamimum Depths Feet
1.	Lagôa dos Patos	9,910	3,825	8.7	24
2.	Lagôa Mirim	3,770	1,455	7.0	21
3.	Lagôa da Mangueira	800	308	7.4	22
4.	Rio Guaíba	500	193	4 (40.)	12 (120)
5.	Lagôa dos Quadros	120	46	5	15
6.	Lagôa Itapeva	110	42	4	12
7.	Lagôa dos Barros	100	38	7 (10)	21 (30)
8.	Lagôa dos Peixes	50	19	3	12
9.	Lagôa Pinguela	40	15	3	12
10.	Lagôa Tramandaí	30	11	2.5	7.5

Within the coastal plain are hundreds of lakes and ponds of varying sizes. Since they represent a characteristic feature of the coastal plain, a simple classification and discussion of the principal types of water bodies is suggested (see Figs. 3 and 4 for locations):

(1) Larger fault controlled lagoons, e.g.,
Lagôa dos Patos
Lagôa Mirim

(2) Smaller fault controlled lakes, e.g.,
Lagôa dos Peixes
Lagôa São Simão
Lagôa Rincão dos Veados

(3) Larger lakes, related to older rocks, e.g.,
Lagôa dos Barros
Lagôa Itapeva
Lagôa dos Quadros

(4) Cordiform (heart shaped) lakes, e.g.,
Lagôa Pinguela
Lagôa Palmital
Lagôa das Malvas

(5) Inlets
Barra do Rio Grande
Rio Tramandaí
Rio Mampituba

The lagoons, Lagôa dos Patos and Lagôa Mirim, are large shallow bodies of water that are connected to the South Atlantic Ocean by a single inlet at Rio Grande (Fig. 4). Although they occupy a large area within the coastal plain, they are relatively shallow water bodies.

The Lagôa dos Patos consists of three distinct parts: The lower Lagôa dos Patos between the Barra do Rio Grande and the Barra da Feitoria (Fig. 4), the central Lagôa dos Patos from Barra da Feitoria to a point near Itapoã, and the upper Lagôa dos Patos consisting of the northeastern part and the pass north of Itapoã into the Guaíba estuary proper.

The lower lagôa is the most difficult to navigate because of its depth, variability and currents. Considerable quantities of flocculated fine sediments are continuously being deposited, causing rapid channel fill which necessitates the continued use of two large dredges.

The central Lagôa dos Patos is the most stable of the three subdivisions of the lagôa, and consequently is commonly navigated by ships drawing up to 20 feet of water. The bottom of this part of the lagoa is floored principally with arkose, and does not require dredging.

The upper (Lagôa do Casamento) part of the Lagôa dos Patos is very shallow and bordered with broad sand flats alternately exposed and inundated with variations in wind direction. Bottom sediments are exclusively medium to coarse sand. The Guaíba estuary which joins the Lagôa dos Patos on the northwest is also an area in instability. Constant dredging is necessary to maintain channels through the deltaic silts and sands deposited by the four streams discharging into the Guaíba.

The Lagôa dos Patos has a very low gradient averaging about 1 meter in 120 kilometers (1 foot in 25 miles). Because of low gradient and relatively minor volume of run-off, waters of the lagôa are almost at a standstill, and wind velocity and direction play a dominant role in the internal dynamics of the lagoons. Distribution of salinity, for example, is primarily controlled by wind direction and intensity. In the Lagôa dos Patos, when strong winds blow from the southeast, brackish water (salts up to 2 p.p.t.) may extend as far north as Itapoã (Fig. 3). However, when the wind blows from north or northeast, fresh water may be encountered between the jetties at Rio Grande. Thus, the Lagôa dos Patos is brackish when the winds are from the southeast and fresh when the winds are from the northeast.

Although only reconnaissance work has been accomplished to date, it is thought that the Lagôa dos Patos was formed when post-Pleistocene faulting occurred along the Mostardas fault zone (Fig. 13). Presumably, a certain amount of tilting of the upthrown block caused a slight depression west of the main fault zone. The actual vertical movement along the fault was apparently enough to block the Guaíba River outlet. Thus, waters which formerly flowed into the ocean from the Guaíba River had no effective outlet and were forced to follow a path along the topographically lower fault-trough between

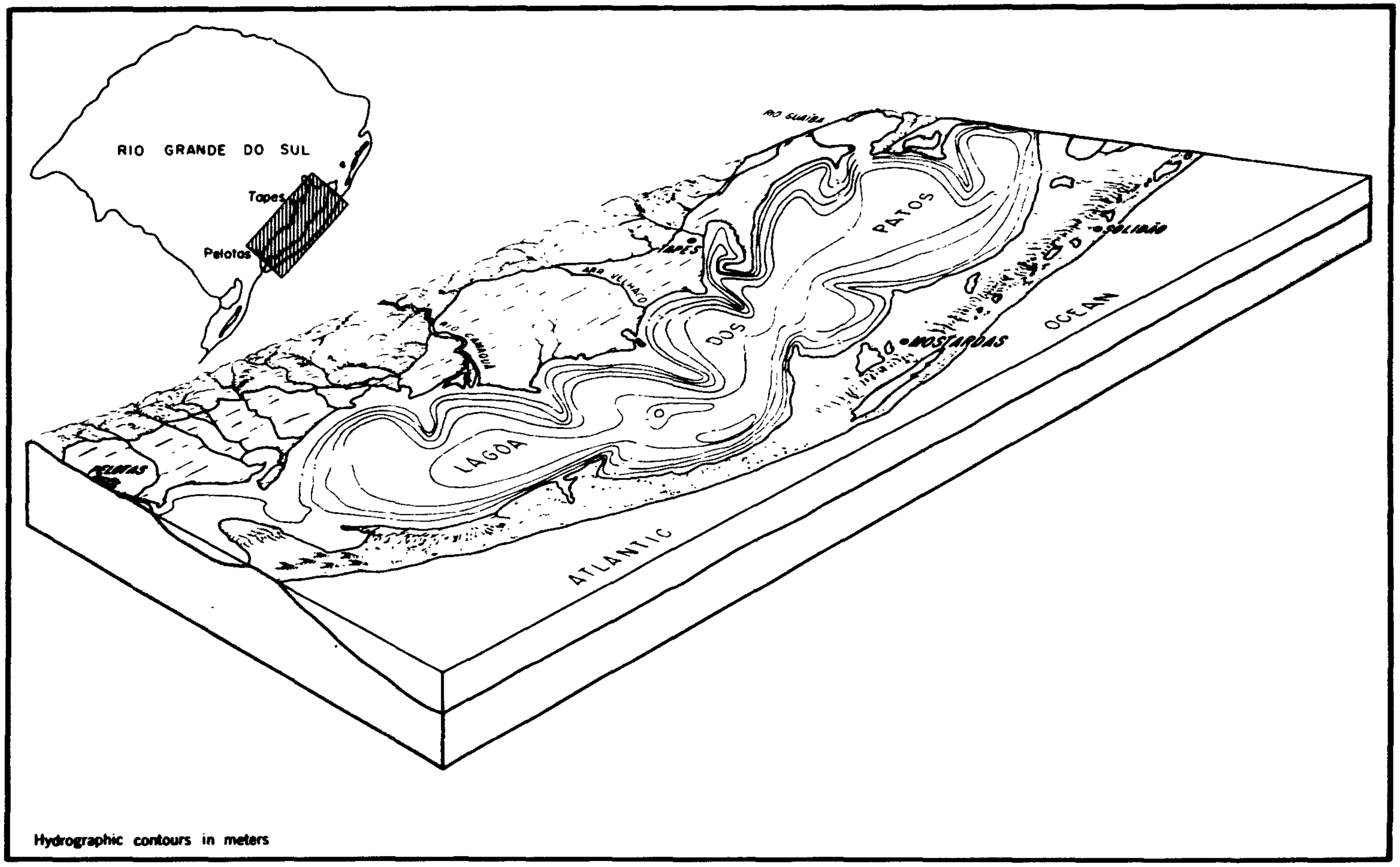


Fig. 13. Block diagram showing the long subaqueous ridges in the Lagôa dos Patos. (Bathymetric curves in meters)

Itapoã and Rio Grande. Because of apparent recency of faulting which originated the trough and the fact that it is essentially at base level, little scouring and erosion has been possible. Hence, the flat bottom-gradient and low water-exchange rate of the entire lagoonal complex.

The two wind-water relationships that are most important are dominant wind direction and fetch. Winds blowing in a constant direction for some period of time over a water body tend to generate waves. These waves have a wider spectrum (relationship between amplitude and period) the farther they are from the initial point where the wind strikes the water body (beginning of the fetch). Thus, where the longest fetch and the greatest intensity of wind directions coincide, the lagôa is deeper and wider. Therefore, since faulting initiated the lake complex and water accumulated, the wind direction and intensity has played the most significant role in determining the configuration and depths within the Lagôa dos Patos (Fig. 13). Several elongate shoals extend in a east-southeasterly direction nearly halfway across the lagôa from the western shore. These seem to be extensions or continuations of the subdued divides that separate the coastal plain west of the lagôa into a series of broad flat valleys. Drainage from the adjacent highlands traverses the coastal plain through several flat, alluvium choked valleys such as that of the Rio Camaquã (Fig. 13). Thus the western margin of the lagôa reflects a drowned estuarine shoreline, more apparent in the hydrography.of the Lagôa dos Patos than in the adjacent subaerial valleys.

Other structurally controlled lakes are present in the coastal plain. These elongate lakes are located on the down-thrown block, east of the Mostardas fault zone near the settlements of Soledade and Mostardas. They are maintained as fresh to brackish lakes by rainfall and by spring water which ascends along the fault zone. Many of these lakes are bounded on the west by the fault scarp, and wind generated waves have tended in some cases to erode and modify the scarp. Lagôa dos Peixes (Fig. 13), the largest of these lakes, is 30 kilometers (19 miles) long and occupies an area of 50 sq. km. (or 19.3 sq. miles). Occasionally, its outlet to the ocean is blocked by longshore drifted sand, resulting in flooding of the lake margins. During the last several years, serious flooding has required continuous dredging operations in order to maintain an effective outlet.

The genesis of the fault controlled lakes is apparently related both to tectonic activity and the presence of large wind drifted dunes. As a result of a tilted fault block, a topographic low was formed east of the fault scarp. In this depression rainfall and spring water collected. Subsequently, beach dune fields developed along the coast impounding water within the enclosed drainage basin. At present the lakes are continuing to enlarge as a result of wind generated waves eroding the loosely consolidated Pleistocene sands which form the western lake shore.

There are three other large lakes in the northern part of the coastal plain: Lagôa dos Quadros, dos Barros, and Itapeva (Fig. 3). The origin of these lakes is not clearly understood; however, they have two characteristics in common: the lakes are bordered on at

least one side by older sediments and their original shape has been greatly modified by the action of wind-generated waves. The Lagôa dos Barros, (Fig. 14) averages less than 8.5 meters, or 28 feet in depth with the exception of a small area along the northern margin of the lake, which could be related to faulting, or which may be a scour hole. In general, the Lagôa dos Barros is pan-shaped with steep edges and a flat bottom. Along the northwest and southern boundaries of the lake the Triassic Botucatú sandstone outcrops, whereas the northern shore is composed of Jurassic basalt talus. This lake has only one effective outlet, a small arroyo at the south, which drains ultimately into the Lagôa dos Patos.

Lagôa Itapeva and Lagôa dos Quadros also show somewhat similar features, i.e., they are faulted, bordered by Triassic semi-indurated sandstone and have few effective outlets. All three of these lakes show important modifications resulting from wave action, which can be related to length of fetch and predominant wind directions. The most important modification is the gentle rounding of the southern portion of these larger lakes. East of the Lagôa dos Quadros and Itapeva there is a complex of multiple sand ridges which are oriented parallel with the present shoreline. These ridges have not been mapped in detail but they seemingly represent continuing coastal accretion.

Cordiform (heart shaped) lakes of Rio Grande do Sul are situated in the northern portion of the coastal plain, principally between the cities of Tôrres and Cidreira (Fig. 2). These peculiarly shaped lakes were first noted and described by Delaney (1960) who applied the term cordiform because of their resemblance to a heart. The relatively small cordiform lakes between Tôrres and Cidreira are so aligned that they have the point of the heart toward the south and the base of the heart farther northward. There are at least 32 heart-shaped lakes within the area of investigation.

It is believed that these lakes were formed in topographically low areas which later developed into small basins of interior drainage because shoreline dune migration gradually blocked all outlets and prevented seaward drainage. In these areas local run-off waters have collected. Wind generated waves from alternate directions during the year resulted in erosion first to one side of the lake and then to the other gradually forming sand beaches around the perimeters of the lakes. Since the fetch in the lakes is small and the wind directions are from varying sectors, the erosive power of the waves is limited; therefore, the bottoms of the cordiform lakes are shallow (max. depth 3-4 meters, but more commonly 2-3 meters).

The wind blows most frequently from the northeast and west (Figs. 11 and 12); therefore, the right, left, and point of the heart are well developed. The base of the heart, which is to the north, is not as well developed because winds from the southern sector are not frequent. These same factors have caused the Lagôa dos Barros, Lagôa dos Quadros, and the Lagôa Itapeva to modify their lower (southernmost) portion and, therefore, look similar to the smaller cordiform lakes (Fig. 3).

There are several double heart-shaped lakes within this portion of the coastal plain. It is believed that this type of

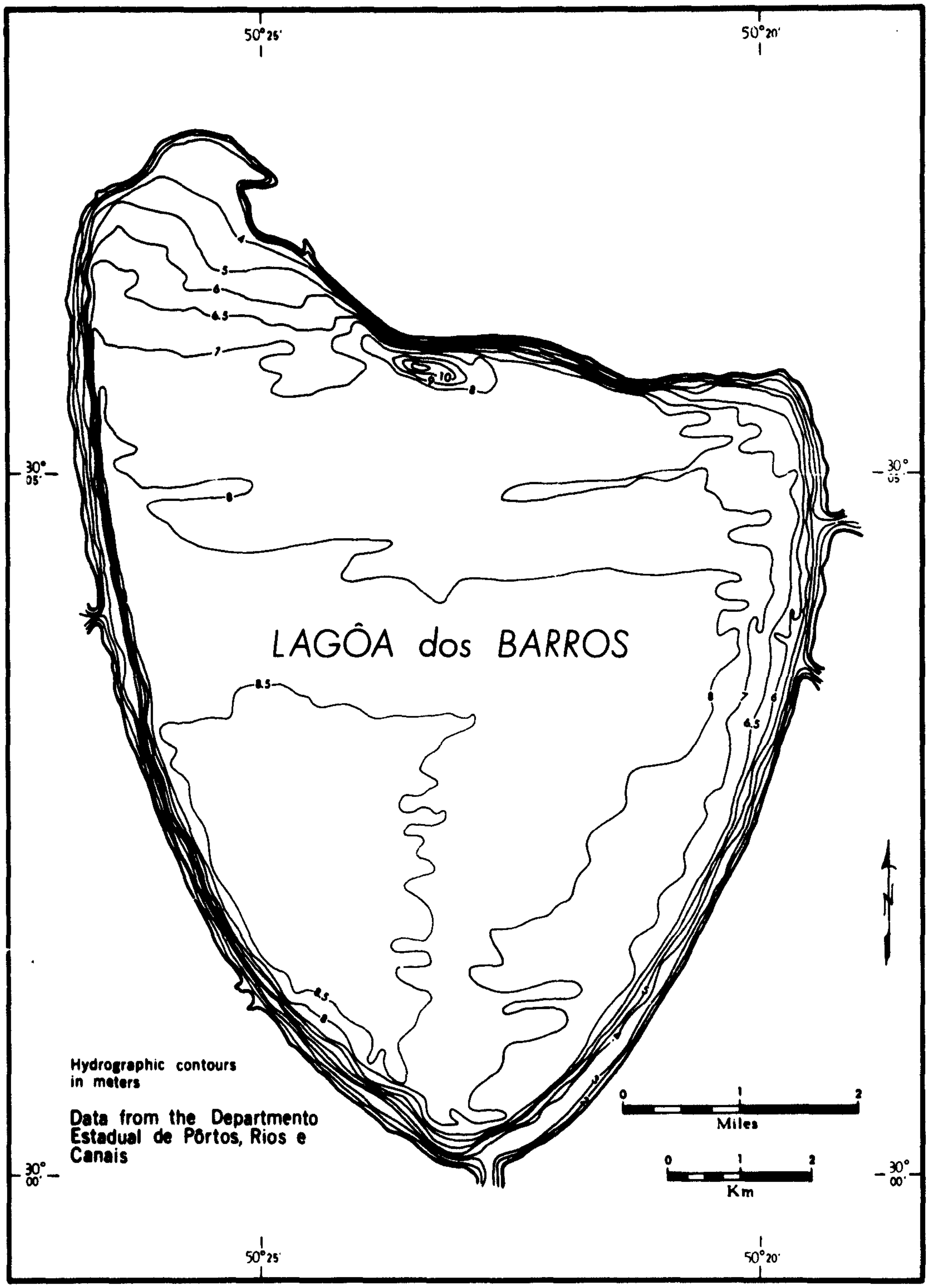


Fig. 14. Bathymetric map of the Lagôa dos Barros.

lake is formed by simple coalescence of two heart-shaped lakes. It seems that cordiform lakes tend to enlarge along the western margin because the winds are dominantly from the east. The general tendency is for the lakes to enlarge slowly and maintain a depth proportionate to wave size. This is true except in the case where the lakes are close to the beach and depths have been affected by wind drifted sand.

There are only three inlets of importance within the area at Rio Grande, Tramandaí, and Mampituba. The inlet at Rio Grande has a sufficiently deep channel (12 to 16 meters, or 40 to 50 feet) to permit large ocean vessels to enter the port of Rio Grande. The channel is maintained artificially which requires the full time utilization of two large capacity dredges for sediment deposition is continuous. Within the inlet salinities vary radically (between 1 and 34 p.p.t.), and when sediment-laden fresh waters from the Lagoa dos Patos come in contact with saline to brackish ocean waters, suspended clays flocculate and settle to the bottom. This flocculation may take place anywhere along the 16 kilometer (9.9 mile) inlet, or as far inland as salt water penetration occurs.

The channel of the inlet tends to remain close to the west bank. Therefore, this area is considerably deeper (12 to 16 meters or 40 to 50 feet) than the east bank, 1 to 2 meters (3 to 6 feet) or less. There are also small tidal bays present in this area. The tidal bays are called "sacos" because their form is similar to that of a sack. Tidal bays such as the Saco da Mangueira (Fig. 4) are shallow, their maximum depth being 2 or 3 meters (6 to 9 feet).

In 1911, 4-1/2 kilometer-long jetties were constructed of granite blocks at the Rio Grande outlet. The jetties have had a pronounced effect on coastal sedimentation processes. Before their construction the river-mouth bar shifted progressively from north to south along the coast. After jetty construction the river-mouth bar has remained more or less fixed and, therefore, has stabilized navigation approaches into the port of Rio Grande.

The inlets have not been studied in detail; however, aerial photographs of the Tramandaí inlet and old maps of the Rio Grande inlet have been studied. In each case the mouths of these inlets have migrated toward the south as a result of southerly longshore drift. This process is discussed later.

The less well-known inlets at Tramandaí and Mampituba will be studied in detail over the next few years by the Departamento Estadual de Pôrtos, Rios e Canais. The discharge rates of the Tramandaí River and Rio Grande are listed on Table 6. There are no quantitative data available for the Mampituba River.

OFFSHORE FEATURES

The South Atlantic Ocean, which borders the Coastal Plain of Rio Grande do Sul, has been studied only superficially. To the north of Brazil and farther south in Uruguay, bathymetric maps with considerable detail have been made by the Brazilian and Uruguayan governments. The only modern maps which contain bathymetric data pertinent

to the coast of Rio Grande do Sul are Cartas 90, 2200, and 2101 of the Marinha do Brasil, and a map of the Tôrres area made by the Secretaria de Obras Públicas do Rio Grande do Sul.

The most significant oceanographic work conducted along the coast of Rio Grande do Sul was done by the German Meteor expedition of 1925. This group of scientists discovered a large subsqueous swell between 30° and 40° South Latitude. This feature, later called the Rio Grande do Sul Swell, is an eastern projection of the mid-Atlantic ridge (Stocks and Wust, 1935). It rises from depths of -4,000 to -5,000 meters (-13,000 to -16,400 feet) to heights of -600 to -700 meters (-1,970 to -2,300 feet). The swell also effectively divides the eastern South Atlantic Ocean into the Brazilian basin to the north and the Argentina basin to the south. Superimposed on the Rio Grande do Sul Swell are plateaus which perhaps indicate ancient basalt or pillow lava flows.

The only other irregularities which rise above the ocean floor are some nearshore reefs composed of shell material. They are normally five or ten meters high and 15 to 20 meters (49-65 feet) below the surface of the ocean.

Figure 15 is a bathymetric chart of the Rio Grande do Sul coast compiled from the maps and charts previously cited. It also includes data obtained from fishermen and sea captains. The profiles show steep slopes at the shelf-break toward the southern part of the area, and a more gentle slope farther north. Detailed data such as fathometer charts or bottom sediment studies are non-existent.

There is only one island along the coast of Rio Grande do Sul. This is the Ilha dos Lôbos, a small basaltic remnant 2 kilometers off the coast at Tôrres. The island is a seaward extension of the adjacent Jurrasic Serra Geral basalts; however, it is not known whether it is an erosional remnant or a resistant part of a downthrown fault block. The island received its name because seals ("lôbos do mar," in Portuguese) and sea lions frequently live there during the winter months. Maximum water depth between the island and shore is 17 meters or 55 feet.

Sediments of the continental shelf are virtually unknown. The few samples studied were obtained by fishing vessels. The fishermen usually note whether the bottom is sand, mud, or rock, but they are seldom interested enough to take a sample or record specifically where they made their observation. Despite the scanty data, several broad generalizations concerning the nearshore bottom sediments may be made:

(1) The greater part of the shallow shelf is apparently covered with sand.

(2) Clay samples studied consist predominantly of illitic clays.

(3) Rocks examined are principally bio-clastic sandstone cemented with aragonite.

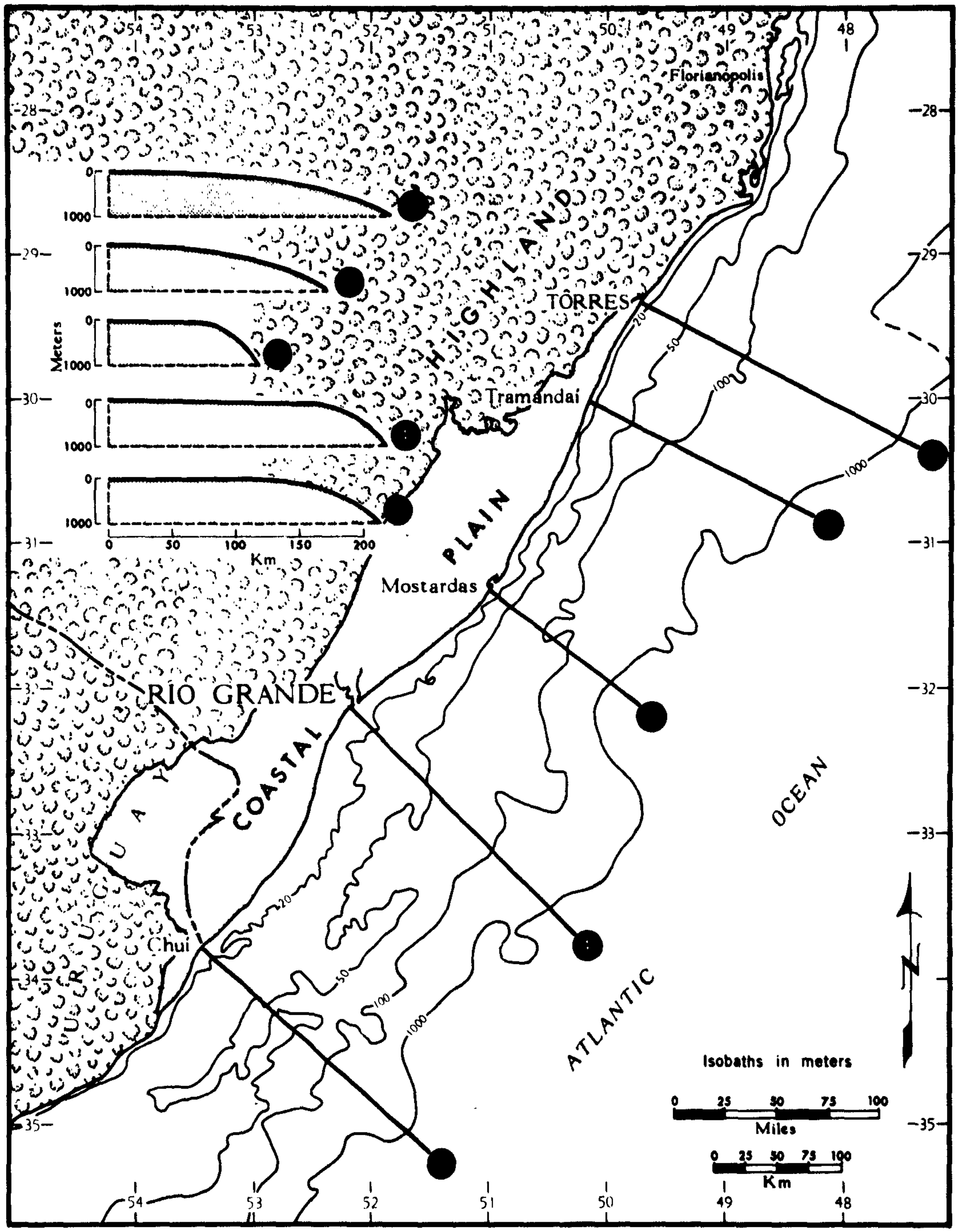


Fig. 15. Bathymetric chart of Rio Grande do Sul coast, with profiles across the edge of the Continental Shelf.

(4) Ironstone (geothite and stipnosiderite has been found. These minerals may have been formed by direct inorganic precipitation.

Salinity data are also very scanty. Figure 16 shows the general salinity distribution pattern for October and November of 1958. Water samples were collected by fishermen and were analyzed by Sr. Boaventura Barcelos, of the Museu Oceanográfico do Rio Grande. The samples were taken during the winter when the north-flowing Falkland current was affecting the coast. The map shows lower salinities toward the south, which perhaps reflect the fresh water influence of the Rio de la Plata.

MARINE CURRENTS AND TIDES

Two major ocean currents, Falkland and Brazil, alternately affect the coast of Rio Grande do Sul. The Falkland (sometimes called Malvinas) is a north flowing, cold water current which is dominant along the coast during the winter months (June-July-August), and the Brazil is a south-flowing, warm water current which affects the coast during summer months (December-January-February). Neither of these currents are especially strong since each is the weaker branch of bifurcated stronger streams (Fig. 17). The Equatorial current is the counterpart of the Brazil current, and the Humboldt stream is the counterpart of the Falkland current. Data published by the Marinha do Brasil (1958) suggest that these ocean currents are actually enormous, weak, eddy currents which reach the shore at widely separated places.

Each ocean current carries a relatively distinct fauna. Frequently on off-shore islands and along the beach, penguins, seals, and sea lions are encountered during the winter months (Fig. 18). This Antarctic fauna obviously moves north with the Falkland current. During summer months, tropical indicators such as the Goose Barnacle (*Leptas anatifera*) are encountered along the beaches of Rio Grande do Sul indicating the influence of the Brazil current. Studies of the fauna of each current are incomplete; however, a recent unpublished study by Buckup (personal communication) of the crabs (Brachyura) in Rio Grande do Sul shows that 44 percent of the species are endemic, 44 percent are typical of the Brazil current, and only 12 percent are typical of the Falkland current. The mollusca belong to a strong antiboreal fauna. Antiboreal is a term used by modern zoogeographers instead of the older term subantarctic (Eckman, 1953).

Other physical factors which are important but almost unknown entities are the storm regime and tidal variation. There are very few storms in Rio Grande do Sul. Wind velocities during storms are seldom more than 40 kilometers (25 miles) per hour and more frequently 20 kilometers (12.5 miles) per hour (Fig. 11). The highest wind velocity ever observed by the Departamento Estadual de Pôrtos, Rios e Canais (personal communication) was 150 kilometers (93 miles) per hour. This, of course, was only once and the duration was very short. Thus, the virtual absence of storms has a pronounced geomorphic effect on the beach, noticeably, a lack of storm berms, nips, notches, and other phenomenon resulting from periodic storm tides.

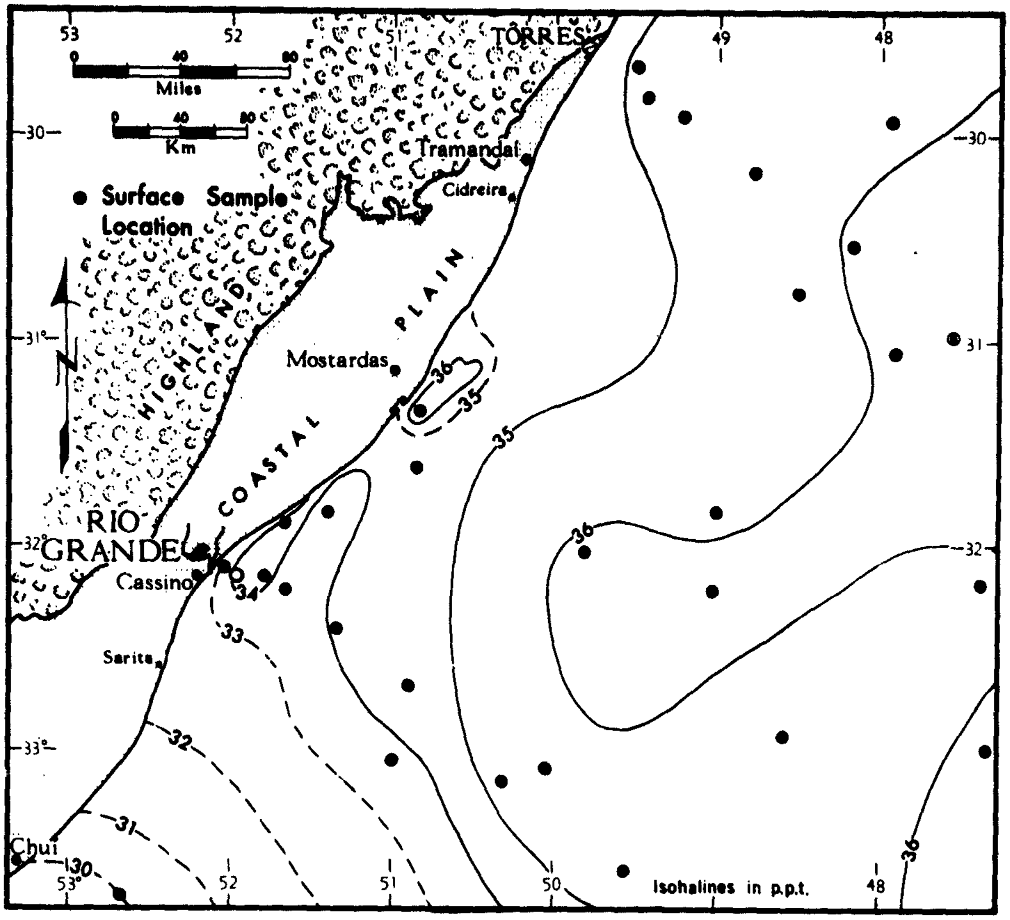


Fig. 16. Salinity distribution map along the coast of Rio Grande do Sul.

The only tide gage in the area is located about 6 kilometers inland (3.6 miles) from the jetties at Rio Grande. Here the tide gage measures the lunar tide plus the apparent wind tide (the effect of the wind on the water). Tide gage readings over the last five years indicate that the average tidal range is 1.20 meters or 3.6 feet. During an exceptional spring tide when the wind was calm, the tidal range measured at Tramandaí (Fig. 3) was found to be 1.5 meters (4 1/2 feet). At that time the littoral zone was 30.46 meters (100 feet) wide and the total swash zone spanned 11 meters (36.1 feet).

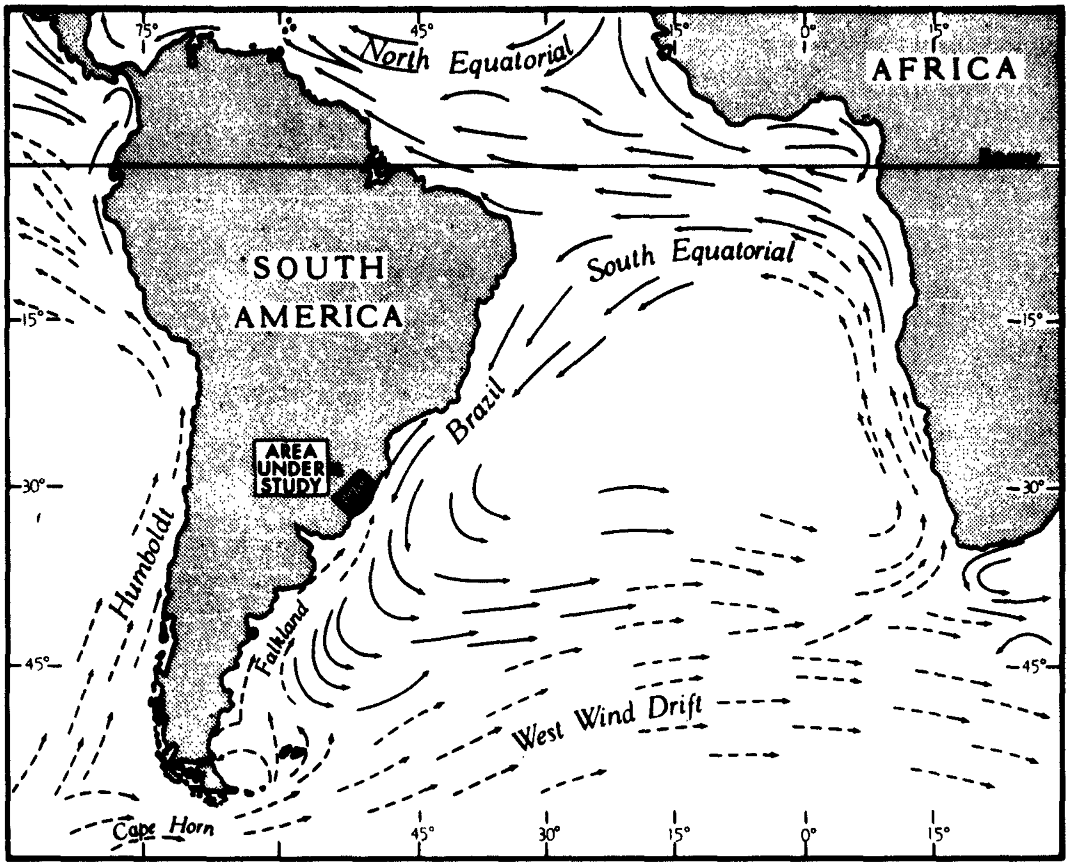


Fig. 17. Sketch map showing the ocean currents along the coast of Rio Grande do Sul (after Atlas of Surface Currents, North Atlantic Ocean).

DISCHARGE RATES OF RIVERS

Discharge rates are important but virtually unknown. Estimates of the discharge rates of the Guaíba River, Barra do Rio Grande and Tramandaí River are listed in the following table. These averages are only approximate, since frequently the wind causes a reverse in the direction of flow of the surface water.

River stages on the Guaíba River at Pôrto Alegre vary within a range of 2.46 meters (or 8.2 feet). At Imbé on the Tramandaí River the range is 1.23 meters (or 4.1 feet) and at Rio Grande it is 1.82 meters (or 6 feet).

Fig. 18. Penguin on the beach north of Itapeva.

TABLE 6

Estimates of Discharge Rates

	Average cubic meters/second (Thousands)	Average cubic feet/second (Thousands)
Tramandaí River	1.3	46
Barra do Rio Grande	20	710
Guaíba River	6.5	230

ASPECTS OF THE FLORA OF THE COASTAL PLAIN

The flora of the Coastal Plain of Rio Grande do Sul is completely different from the coastal flora of South America south of the Orinoco River. The Rio Grande do Sul flora is more varied both in individuals and species; furthermore, there is no mangrove or coastal forest present. Phytogeographic map studies of the coastal plain have not been made; however, P. Balduíno Rambo (1956) has published a general description of the coastal flora. Based on this publication and on field observations the following table has been constructed.

TABLE 7

Important Plants of the Environments within the Coastal Plain of Rio Grande do Sul

A. Ocean

Phaeophycidae (brown algae)
Rhodophycidae (red algae)

B. Breaker zone

Phaeophycidae (brown algae)

C. Littoral

Transported forms

D. Sand Beach

Sesuvium portulacostrum
Salicornia gaudichaudiana
Spartina sp.

E. Dune field

Sesuvium portulacostrum
Cotula coronopifolia
Alternanthera sp.
Heliotropium curassavicum
Panicum reptans
Solanum sisymbrifolium
Hyptis labiadas
Ficus subtriplinervia

F. Lakes and ponds

Chlorophycidae (green algae)
Eichhornia azurea
Eichhornia crassipes
Eichhornia grandiflorus
Salvinia auriculata
Azolla filiculoides
Wolffiella sp.
Lemna sp.
Pontederia cordata
Regnellidium diphyllum
Heterontherea sp.
Utricularias insetivoras
Jussieua sp.
Lycopodium inundatum
Ranancuius sp.
Drosera brevifolia
Eryngium cobrem
Erythrina crista-galli

G. Sand plain

Andropogon leucostachyus
Cenchrus tribuloides
Paspalum sp.
Fimbristylis complanata
Killinga pungens
Hydrocotyle umbellata
Centell asiatica
Eryngium nudicaule
Bromelia faustuosa
Cordia trichotoma
Cedrela fissilis
Tamarix gallica

In the first two zones (ocean and breaker) algae constitute the significant flora. Microscopic brown algae frequently are sufficiently abundant to give the ocean a "dirty" color. Red algae, most frequent near Tôrres, may be carried south for great distances by longshore currents and, therefore, can be used as a guide to indicate strength of littoral drift and effectiveness of Brazil vs. Falkland currents.

In the littoral zone only forms which are not "in situ" are normally found. Most common are drift wood and transplanted vegetation. Frequently water lilys in large masses are transported to the ocean. When they come in contact with saline water they die and are later washed up on the beach. The only stable vegetation in the littoral zone of Rio Grande do Sul are marine algae at Tôrres.

The sand beach has no impoverished fauna because of the magnitude of wind drifted sediment. The most important genus is *Sesuvium*. *Salicornia* also occurs in this zone, but it is not as important here

as on many other coasts.

The dune field has a very distinctive vegetative assembly. Typically grasses and trees are important in this zone. The grasses are most abundant in the zone of active sand movement and trees (principally the "figueira," Ficus subtriplinervia) characterise the zone of fixed dunes.

The region of lakes and ponds has an abundant flora, the most important forms being listed in Table 7. A typical association near fresh water or stagnant ponds include: a dense carpet of green algae in the water, rushes or "junco" near the edges, with leguminous plants growing on the firm soil and contorted bushes forming low brushy areas.

The sand plain is characterized by grasslands and round groups of trees called "capoes baixos." The soil in this zone is usually firm and dry which enables the forms listed in the table to establish a rather typical landscape.

Most common of the artificial vegetation in the coastal plain of Rio Grande do Sul is the eucalyptus tree. These trees are usually planted in rectangular groves and are used primarily for fire wood as well as wind breakers and shelter for sheep and cattle.

PHYSICAL GEOLOGY OF THE COASTAL PLAIN

The salient physical features of the coastal plain are areas of: 1) the older rocks, 2) Pleistocene sands, 3) the Recent sand plain, and 4) modern beaches. Each of these divisions has its own peculiar set of characteristics and, therefore, will be discussed separately.

OLDER ROCKS

The surface contact between the older rocks (pre-Quaternary) and the younger sediments (Quaternary) forms the interior limit of the Coastal Plain of Rio Grande do Sul (Fig. 7). An understanding of these older rocks is essential to the comprehension of the geologic setting of the coastal plain because they have played an important role in furnishing detrital material for the Quaternary sediments.

Pre-Cambrian crystaline rocks, a part of the Brazilian shield, locally form the eastern margin of the highlands known as the "Escudo Riograndense". They are principally granites, granitized sediments, schists, and gneisses, which outcrop in an arcuate belt from Pelotas to Itapoã. Farther north they are faulted along the eastern margin of the Coxilha dos Lombos (Fig. 3) where only rare outcrops of granite or gneiss are found.

North of the Lagôa dos Barros (Fig. 3) a Triassic eolian sandstone crops out. This sandstone, the Botucatú formation, consists of pink to reddish, fine-grained, angular to sub-angular, well, sorted, cross-bedded quartz sand. Certain zones of this sandstone are highly silicified. Thin-sections reveal the presence of microcline and plagioclase. These grains are normally so altered that they are more properly considered to be kaolinitic clay, and form the cementing material of the sandstone. Heavy minerals present in these Botucatú outcrops are tourmaline, zircon, and staurolite.

Disconformably overlying the Botucatú in the same area and farther to the north are the classic Serra Geral basalt flows. This formation is more than a kilometer thick and locally is composed of as many as thirteen distinct flows. These rocks form a sharp, abrupt escarpment along the inner limit of the coastal plain from Osório to Tôrres (Fig. 8). There are only two localities in Eastern South America where the basalt reaches the sea; they are Tôrres and Itapeva (Fig. 3).

In the subsurface overlying the pre-Cambrian along the west side of the Lagôa dos Patos a fine-grained, greenish, fossiliferous sandstone of Tertiary age has been encountered in two recently drilled test holes. This formation overlaps the crystaline basement

and is covered by more than 100 meters (328 feet) of younger continental sediments. Preliminary studies of the fossils indicate that these sediments were deposited in a near-shore, marine environment. This formation does not have a name, nor does it outcrop on the surface in the area studied.

YOUNGER SEDIMENTS

Since the work of Carvalho (1933), all described sediments in the Coastal Plain of Rio Grande do Sul have been considered to be of Recent age. This denomination has always been used very loosely and applied to all non-consolidated sediments. During the course of field work in the coastal plain, the writer has been able to delineate certain lithologies and surfaces of which some are Pleistocene and others are Recent. The sediments are principally sand size; however, minor amounts of clay, silt and gravel also have been encountered. Pleistocene surfaces stand out on the air photographs as higher, better drained land, whereas Recent surfaces are lower and more sodden. Tonal effect is almost the same on aerial photographs for the Pleistocene and Recent, since a thin veneer of Recent sediments usually covers the Pleistocene.

Pleistocene sediments may usually be differentiated from the Recent sediments in the following manner:

(1) They are more highly oxidized, hence more reddish or yellowish in color;

(2) They contain more clay-size particles and are more consolidated;

(3) Pleistocene surfaces usually stand at higher elevations than Recent sediments.

Pleistocene -- The Pleistocene of Rio Grande do Sul is subdivided into three basic groups of unconsolidated sediments; (1) saprolites, (2) arkose, and (3) quartz sand. Saprolite is defined here as a general name for the thoroughly decomposed, altered, but untransported material which overlies bedrock. The saprolites in the area are mostly decomposed granite. Arkose is used here to describe a sediment which is essentially composed of large grains of clear or milky quartz, and grains of microclinic feldspar in a matrix of sandy clay. Additionally, the arkose is poorly sorted and is derived from acidic igneous rocks of granitoid texture. It is formed by mechanical disintegration. The quartz sand is a siliceous detrital deposit which is well-sorted, unconsolidated, and consists predominantly of quartz particles within the size range of 2 to 1/16 mm. in diameter.

Saprolites occur along the inner limit of the coastal plain, overlying the ancient rocks of the area. The most common type of saprolite encountered in the area is "grus," (an accumulation of fragmental products derived from the weathering of granite "in situ"), others are saprolites formed from schists, gneisses and phylites. This sediment overlies the parent rock and can be differentiated from it only by the degree of consolidation and alteration. The saprolites

are always "in situ" and may have a thickness up to 40 meters (or 131 feet), particularly in cases where the saprolite is grus formed from coarse grained granite. It seems, although it is not proven, that these deep zones of saprolite are principally Pleistocene in age, since elsewhere in Rio Grande do Sul Pleistocene mammals have been found in comparable grus deposits. Occasionally, discontinuous "hard pans" occur within the saprolite. These and other ferro-magnesian secondary deposits (ironstones, etc.) are undoubtedly related to the action of ground water. The saprolites produce a podsolic type soil which is stony, but develops a grass cover to form good grazing lands.

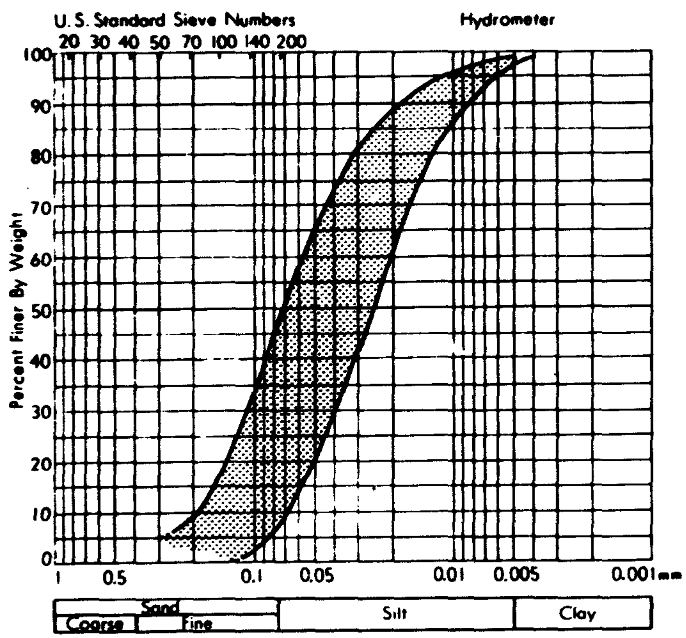
The arkose overlies and overlaps the Tertiary west of the Lagôa dos Patos and in subsurface as far north as the Coxilha dos Lombos (Fig. 3). The principal difference between arkose and grus is that the former has been transported downslope (largely by colluviation or mass movement). From observations of several bottom samples, it appears that this unconsolidated sediment underlies at least a part of the Lagôa dos Patos. The thickness of the arkose varies between a few meters to more than a hundred. Recently two stratigraphic tests made by Petrobás near Camaquã (Fig. 4) encountered approximately 100 meters (328 feet) of this material.

In an effort to determine more exactly the precise nature of the Pleistocene and Recent sediments numerous granulometric analyses were made. Conventional sieve separations were used for the coarser material, and hydrometer methods were utilized for the finer fractions. Binocular and petrographic microscopes were employed in the morphoscopic, textural, and heavy minerals studies of the sediments. Differential thermal analyses and X-ray techniques were utilized for several clay mineral determinations. All of the grade sizes are stated in terms of the Wentworth system.

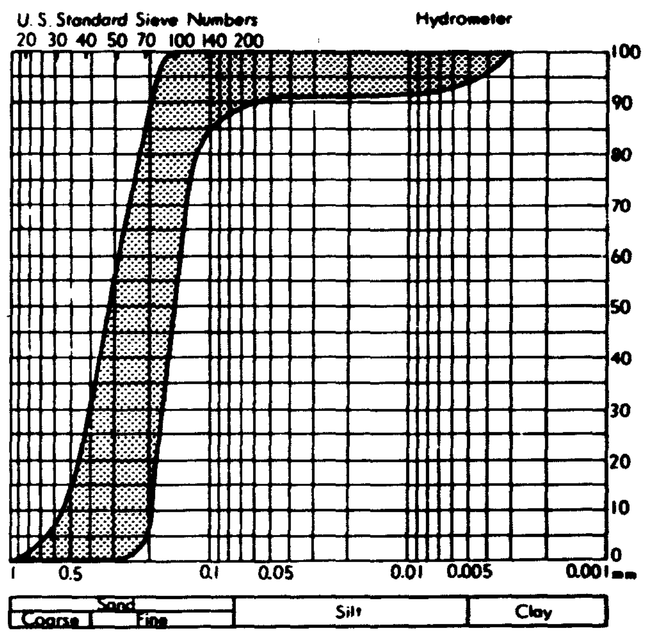
The arkose is composed of unconsolidated sand, silts, gravels and clays. It has been derived from the older crystalline granitoid rocks, and is united mechanically into a mass of unsorted, unconsolidated sediments, differing only slightly from the mother rock. The arkose is basically composed of large (up to 1 cm.) grains of clear to milky quartz, and somewhat smaller (1/2 cm.) grains of microcline feldspar in a matrix of plastic, sandy to silty clay of red, gray or yellow color. The clay fraction occasionally is almost pure kaolinite.

Although the constituant minerals of the saprolite and the arkose are the same, the arkose may be differentiated from the saprolite because it consists of finer, transported particles, and is somewhat better sorted. Figure 19 is a composite of six grade-size analyses made from cores at depths of 9-12 m, 33-35 m., 44-45 m., 53-56 m., 76-78 m., and 96-102 m. in well Ga-st-Rs-1, a stratigraphic test made by Petrobras, west of the Lagôa dos Patos at Graxaim (Fig. 4).

The arkose overlies and overlaps Tertiary beds west of the Lagôa dos Patos. This contact seems to be gradational; however, difficulties were encountered in defining the base of the arkose, since the contact is not exposed on the surface, and the only evidence available is in cores from the two Petrobras wells.



Composite cumulative curve of six anaylsis of arkose. From 9-12m., 33-35m., 44-45m., 53-56m., 76-78m., and 96-102m., in test boring Ga-st-1 RS (Petrobás) near Graxaim.



Composite cumulative curve of 20 analysis of Pleistocene quartz beach sands.

Fig. 19. Grain size analysis of the Pleistocene arkose.

Fig. 20. Cumulative curves of the Pleistocene quartz sands.

In a continuing sequence of overlapping sediments, the arkose is presently overlapped by a thin layer of Recent sand (from 25 centimeters to two meters thick) west of the Lagôa dos Patos. This veneer of Recent sand is being actively transported and sorted by the wind throughout the year.

Reddish-yellow, semi-consolidated quartz sands occur in scattered outcrops near Rio Grande, Mostardas, Cidreira, and the Lagôa dos Barros (Fig. 3). These sediments apparently are Pleistocene beach sands which have been uplifted by faulting. Although they have approximately the same grade-size as Recent sands (Fig. 20) they may be differentiated from them in the following ways:

(1) Pleistocene quartz sands are normally quite well compacted, semi-consolidated sandstone, in contrast to Recent beach sands which are unconsolidated.

(2) Pleistocene beach sands are well oxidized. They are red, reddish-yellow or tan, have a mottled appearance, and frequently contain ferruginous nodules or "hard pan." Recent beach sands are normally white to yellow, unoxidized, and frequently contain layers of black sand (magnetite, ilmenite, and other opaque minerals), whereas the Pleistocene sands do not commonly exhibit layers of opaque heavy minerals.

(3) Pleistocene sands usually stand topographically higher than the Recent dune sands. Where they are exposed topographically lower than the Recent dune sands (such as in Areias Gordas) they tend to form huge erosional amphitheater.

(4) Pleistocene sands have a higher clay content than Recent sands. This is probably due to the chemical breakdown of the feldspars into clay minerals.

(5) Muscovite present in Pleistocene sediments has been altered but retains a fresh appearance in Recent sediments.

The grain size, sorting, frosting, roundness, etc., of Pleistocene quartz sand indicates that it was once a beach sand. The only fossils present in these sediments are remains of terrestrial mammals; evidence that does not disagree with the interpretation of an ancient beach environment.

Recent -- The Recent sand plain is by far the largest physiographic division within the Coastal Plain, extending from the inner escarpment of the coastal plain to the foreshore of the beach. The sand plain is predominantly flat lying and maximum elevations are generally low (less than 20 meters, and normally about five). There are many large dune fields and active dunes within the area. Some older vegetated stabilized dunes form the higher elevations in the coastal plain. The Recent sand plain shows characteristic pockmarks on the aerial photographs which are slight depressions in the sand plain where water collects during the rainy season.

The Recent sand plain is characterized lithologically by vast quantities of fine sand with only minor occurrences of silt and clay. The fine sand overlaps all other rocks in the area. Thus, at Tôrres (Fig. 3) fine sand is found overlying basalt; west of the Lagôa dos Patos it overlies arkose and granite bedrock; and near Areias Gordas it overlies consolidated Pleistocene sands (Fig. 4).

Approximately forty mechanical analyses of the sand were made. The samples were collected from localities at five kilometer intervals along the shoreline. Results of the sand analyses are listed below and are presented graphically in Figure 21:

(1) Medium to fine grained, median diameter = .18 mm.

(2) Well sorted, So = 1.10

(3) Most grains frosted and/or polished

(4) 85-90 percent of the grains are well rounded; however, some grains (5-15 percent) are broken or chipped

(5) Grains are not cemented and do not show iron stains

(6) Heavy mineral suite, 1-2 percent of total, consist of:

Zircon	Andalucite	Epidote
Tourmatine	Hornblende	Apatite
Rutile	Actinolite	Kyanite
Garnet		

(7) Normally, muscovite in the light fraction is unaltered.

Occasionally a sandy clay is found along the beach. Most frequently this material is found at Cassino, near Rio Grande (Fig. 4), and at Barro Prêto, south of Tramandaí (Fig. 3). The "clay" on analysis is found to consist of 50 percent clay, 31 percent fine sand, 16 percent silt, and 1 percent medium sand. The dominant clay mineral is illite. No fossils were found in the material at Barro Prêto. The sandy clay near Cassino, on the other hand, contains a rich microfossil assemblage, the most imprtant genera including <u>Elphidium</u>, <u>Nonionella</u>, <u>Eponides</u>, <u>Cibicides</u>, <u>Nonion</u>, and <u>Quinqueloculina</u>. The sandy clay lies conformably over the quartz beach sand and extends along the beach for several kilometers. It is approximately 75 cm. to 1 meter (3 feet) thick (Fig. 22), and 50 meters (164 feet) wide. It is believed that this material was originally transported in fresh water in the Barra at Rio Grande (Fig. 4). Upon leaving the Barra, the sediment laden fresh waters came in contact with saline waters of the ocean resulting in flocculation of the clays. Since the wind is dominantly from the northeast the prevailing littoral drift transported the flocculated clay to the beach at Cassino where it was deposited probably under the influence of a minor storm, in thin layers over the beach sands (Fig. 23). The clay mass overlapping the beach sand at Barro Prêto (Fig. 24) has a comparable relationship to the Rio Tramandaí some six kilometers north. Similar occurrences of transportation and deposition of clay masses have been reported by Morgan, Nichols and Wright (1958) on the Louisiana Coast.

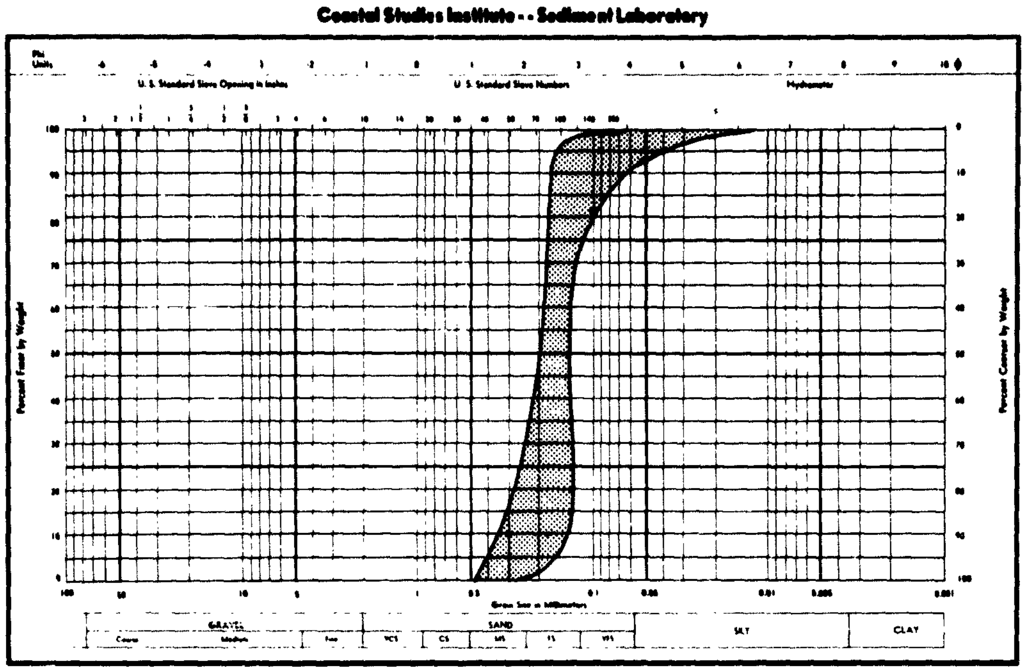


Fig. 21. Cumulative frequency curve of forty samples of Recent quartz sand taken from localities separated by at least five kilometers along the strand line of the study area.

Fig. 22. Clay deposits at Cassino.

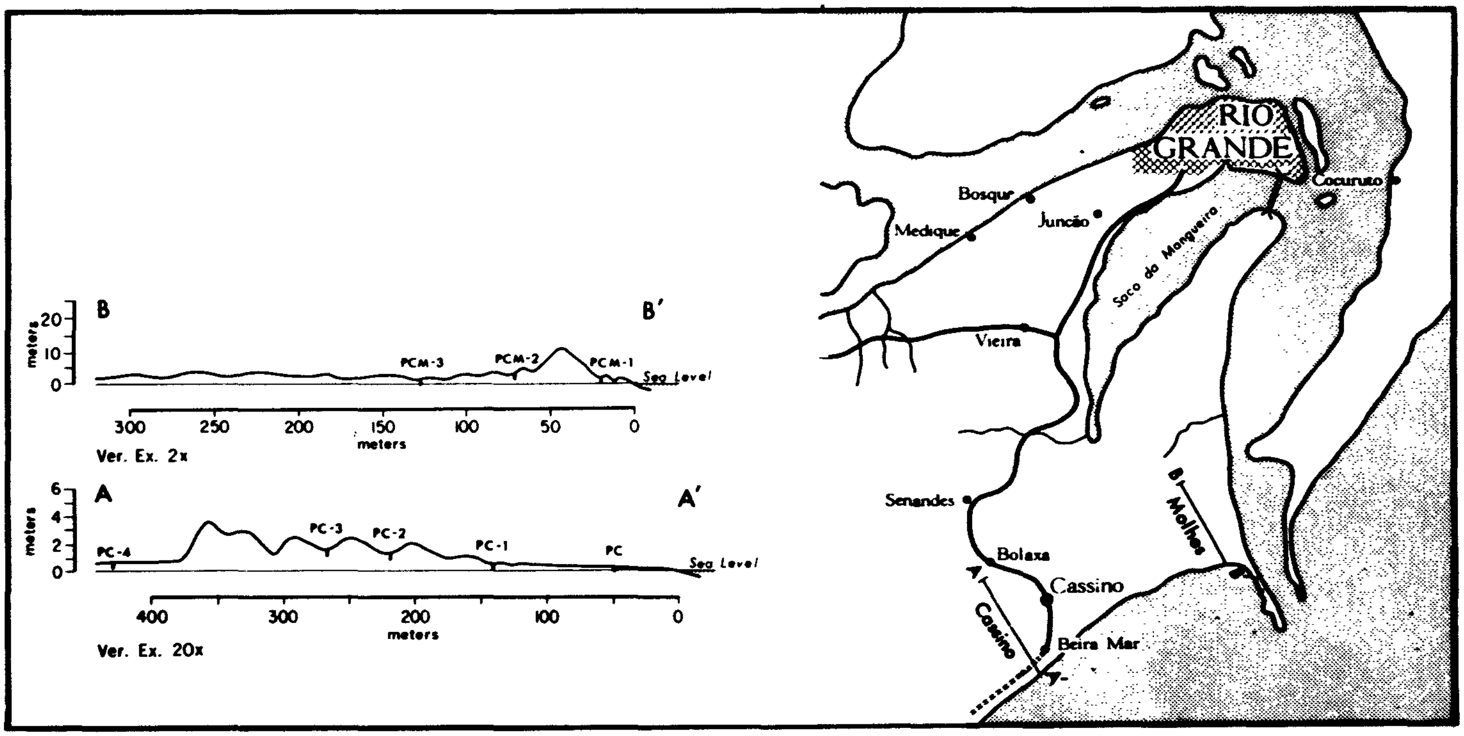


Fig. 23. Sketch map and beach profiles of Rio Grande - Cassino area.

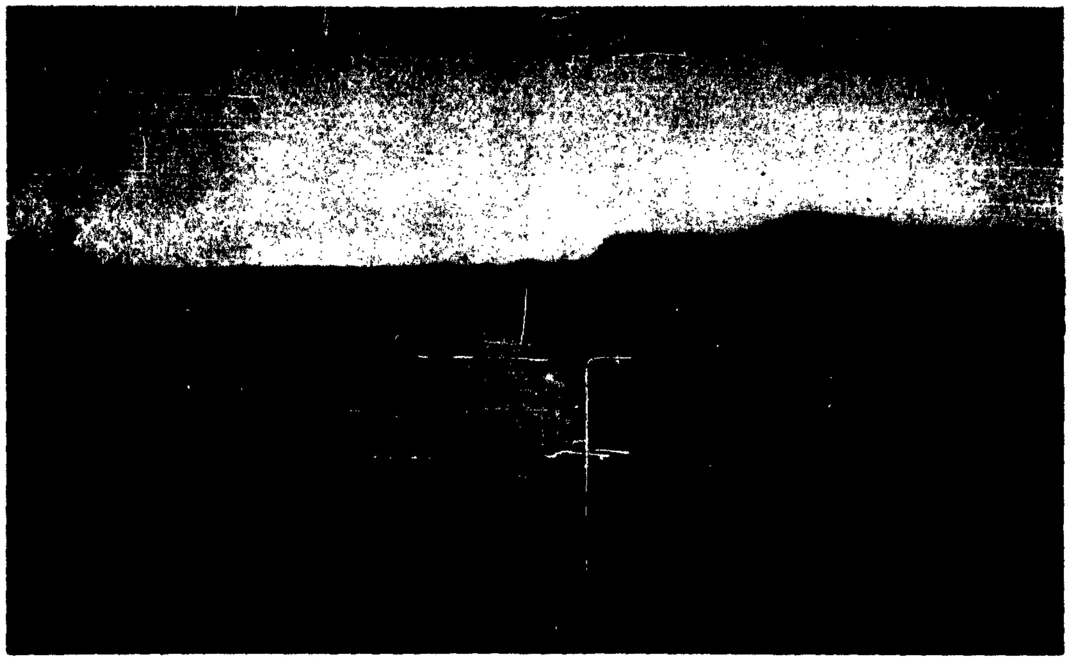


Fig. 24. Clay deposits at Barro Prêto.

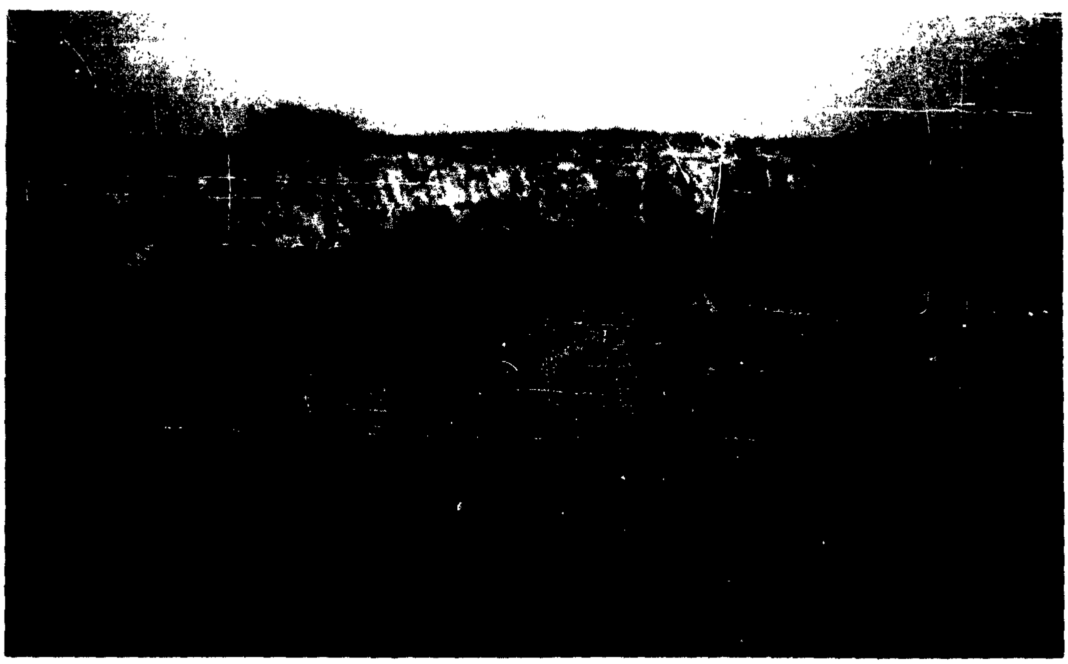


Fig. 25. Breeches in beach near Capao da Canoa.

Ocean beaches have been formed along 620 kilometers (384 miles) of coastline in Rio Grande do Sul. These beaches vary in width from 100 to 1,000 meters (strand line to dune field). In general, beaches are progressively wider toward the south. The dip or slope of the beach face is 3 to 5 degrees (Fig. 23).

The beaches are composed of fine- to medium-grained, well rounded, white to yellowish sand. Beach sands normally range from .12 to .25 mm. in diameter with a median of about .18 mm. The sorting coefficient normally ranges 1.08 to 2.05, and averages 1.10 for beach sands at the strandline. The total ranges of cummulative curves of grain size analysis are shown on Figure 21.

Occasionally, zones of black sand are encountered along the beach. These zones are seldom more than a few millimeters thick and several meters long. The heavy mineral suite of the black sands consists of 35-50 percent opaque minerals (magnetite, ilmenite, titano-magnetite, etc.); the remainder consisting of non-opaque minerals (zircon, tourmaline, rutile, biotite, andalucite, hornblende, actinolite, epidote, apatite, garnet, and kyanite).

The tendency is for the number and kinds of metamorphic minerals to increase northward, perhaps indicating a metamorphic source area to the north, since rocks containing such high-grade metamorphic suites are not known in Rio Grande do Sul. If this is true, then, perhaps beach sands are generally in transit from north to south. This phase on the problem is still only a matter of conjecture and needs more intensive investigation.

The most important sedimentological problem of the coastal plain is an understanding of the origin of this enormous fine sand mass. The obvious source of such a large quantity of fine sand is the Botucatú sandstone, which is known to outcrop in the northeastern portion of the coast (Fig. 8) and perhaps crops out subaqueously on the Rio Grande do Sul Swell, discussed previously. Approximately 60 random samples of Botucatú and Recent beach sands were analysed for comparison purposes as shown on Table 8.

From these data it appears that the Recent beach sands consist of a mixing of the Botucatú heavy mineral suite and another metamorphic suite which has perhaps been derived from the crystalline rocks of the "Serra do Mar" farther north. Further granulometric and heavy minerals studies of these two sands should be made to determine if the divergence of median diameters, sorting coefficients and heavy mineral suites (Table 8) may be due to a mixing of materials from two distinct source areas.

TABLE 8

Comparison of Botucatú and Recent Sands
Coastal Plain, Rio Grande do Sul

	Botucatú Ss. (Triassic)	Beach Sand (Recent)
Median grain size (mm.)	.12 - .27	.15 - .33
Sorting coefficient	1.23 -1.59	1.08 -2.00
Heavy mineral content	Tourmaline Epidote Garnet Kyanite Zircon Rutile	Tourmaline Epidote Garnet Kyanite Zircon Rutile Andalucite Hornblende Actinolite Tremolite

The normal beach slope and offshore profile is exceedingly flat. During calm periods the beach slope is 2° or 3.4 meters in 100 meters. Offshore profiles made by the Departamento de Pôrtos, Rios e Canais south of Tramandaí (Fig. 3) show that the subaqueous slope is 3° 27' or 6 meters per 100 meters (Profiles, Fig. 15).

There are normally two to four rows of breakers along the coast of Rio Grande do Sul. They are usually spilling breakers in contrast to the more normal plunging type and average 0.5 to 1.5 meters (1.5 to 4.5 feet) high. Waves derived both from sea and swell occur along the coast. Wind generated waves have a period of approximately 5 seconds, whereas the swells have a period of about twice that length.

On two separate occasions, stakes were set at Tramandaí (Fig. 3) to establish the littoral zone of the ocean and the tidal range. In both cases measurements were made over a 24 hour period. The average of these measurements show that at Tramandaí, on calm days, tidal range is 1.5 meters, or 4.5 feet. The littoral zone of the ocean is 30.5 meters, or 100 feet, wide.

An interesting fact about the beaches in Rio Grande do Sul is that even though the beaches are completely unprotected, there are almost no berms or storm beaches, obviously because of the lack of real storms. In Cidreira, summer beach houses which were constructed almost 50 years ago, less than 100 meters (328 feet) from the open ocean, are still standing.

The uniformity of the beach is interrupted by breaches or breaks ("sangradouros" in Portuguese) which form during the rainy seasons. These small channels originate during periods of heavy

rainfall when the water table within the dune field becomes higher than sea level and eventually breaks through the beach (Fig. 25). Water seeps through the beach until it finally begins to scour the sand and transport it to the ocean, causing channels up to a meter deep and several tens of meters wide. These channels exhibit a distinctive braided pattern. During the rainy winter months such breaches are sufficiently numerous to disrupt vehicular traffic along the beach. On a one-day trip from Imbé to Tôrres, a distance of some 80 kilometers (50 miles), 200 such breaks were present. Crossing these scour channels is time consuming and effectively reduces traffic along the "Estrada da Praia" during winter months.

A comprehensive analysis of the coastal fauna was not possible; however, some of the fauna was collected and identified, at least generically. The following list of foraminifera are all common antiboreal open beach forms, and are arranged in order from most common to rare: Elphidium, Nonionella, Eponides, Quinqueloculina, Discorbis, Triloculina, Globigerina, Cibicides, Nonion, Bolivina, Bulimina, Sorites.

Along the beach a varied molluscan fauna exists. The dominant genus present is Donax. Other important genera are: Mytilus, Pitar, Hutricula, Tivela, Barbatia, Arca, Mactra, Olivancillaria, Buccinanops, Trachycardium, Ostrea, Tagelus, Pecten, Amiantis, Tonna, Dorsanum, Crepidula, and others of less importance. Other elements of the fauna such as fish, plankton, etc., were not classified.

The most important physical factor influencing the morphology of coastal plain is wind and its effects upon sediments. Wind directions and intensities have previously been discussed; however, the extreme importance of this process as a geomorphic agent must again be emphasized. Morphologically, wind action forms large dune fields along the entire coast, deposits elongate tongues of sand, spreads a thin veneer of sand over the older rocks, modifies the shape and depth of water bodies and hinders the growth of beach vegetation.

There are many well developed dune fields along the beach, the largest near Mostardas being some 12 kilometers (7.5 miles) wide. However, the dune fields normally vary between five hundred meters and 6 kilometers in width. Normally, the dune fields are narrower toward the north and wider in the southern portion of the coastal plain.

Dune elevations vary between 10 and 25 meters (33 to 83 feet), sief dunes normally being higher than barchan type dunes. For comparison purposes a number of dip measurements were made on barchan dunes near São José do Norte. Data are tabulated as follows:

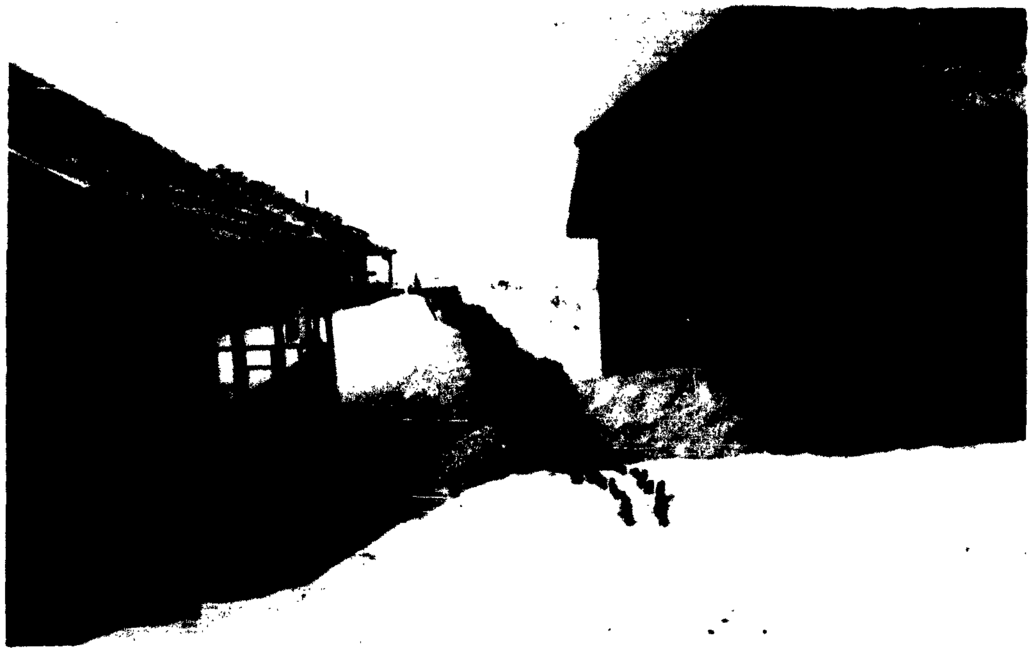


Fig. 26. Sand around beach houses, Cedreira.

Fig. 27. Wind fences to stop sand movement.

TABLE 9

Dip Measurements
Barchan-type Dune Area near São José do Norte

	LEEWARD SLOPE		WINDWARD SLOPE	
	Angle of Dip	Frequency	Angle of Dip	Frequency
	25°	1	0°	4
	29°	4	1°	5
	30°	3	2°	3
	31°	5	3°	3
	32°	6	7°	3
	34°	1	8°	2
Average	30°10'	20(Tot.)	3°30'	20(Tot.)

Occasionally wind-drifted sand surrounds or covers beach houses (Fig. 26). In more populated sectors of the beach, wind fences have been constructed to modify or halt sand movement (Fig. 27).

The numerous elongate tongues of wind blown sand which occur along the coast, are in a sense natural wind roses of the Recent because they are aligned with the dominant wind direction. This relationship is illustrated on Figure 28 which is a tracing of a sand tongue from an aerial photograph taken near Mostardas (Fig. 4) with wind rose of Mostardas (Fig. 12). Thus, it can be seen that the long tongues of sand aligned in a northeasterly direction are directly influenced by the dominant wind direction in the Coastal Plain of Rio Grande do Sul.

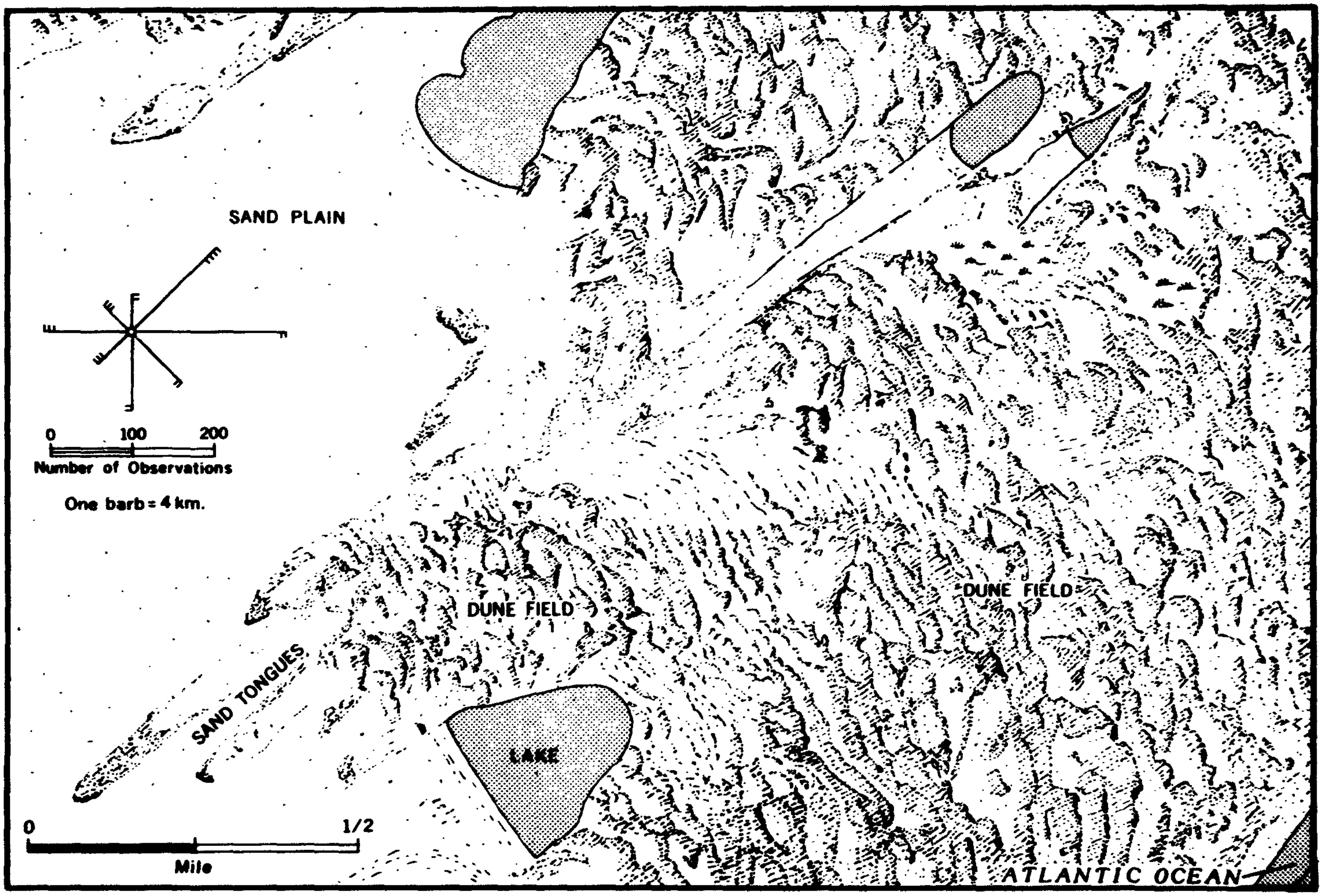


Fig. 28. Comparison of sand tongues and wind rose of Mostardas.

GEOLOGIC HISTORY

OLDER ROCKS

An examination of the geologic map (Fig. 8) shows that the inner limit of the Rio Grande do Sul Coastal Plain is everywhere formed of ancient rocks (pre-Cambrian to Jurassic), and the sediments which comprise the surface of the coastal plain are Quaternary in age.

The crystalline rocks of the area are generally considered to be pre-Cambrian. These rocks have not been studied in detail; however, some of them are obviously granitized sediments while others seem to be intrusive. The schists are predominantly high-grade metamorphics, and the gneisses are principally "augen" types. Most of these rocks have been faulted or folded since their formation in pre-Cambrian time. Structurally these rocks belong to one of the southernmost extensions of the Brazilian Shield, which occupies an extremely large portion of Eastern South America, extending from the Amazon basin to the Rio de la Plata (Fig. 1).

In Rio Grande do Sul, a long period of time separated the formation of pre-Cambrian rocks and the first deposition of Gondwana sediments. This hiatus is estimated to have extended from Lower Cambrian to Upper Carboniferous or Lower Permian. The Gondwana sediments were deposited disconformably over the ancient crystalline rocks. These sediments had site-of-deposition environments as varied as glacial, swamp, tidal flat, continental lake, and desert (Delaney and Goñi, 1961).

The Gondwana sediments of southern Brazil are capped by thick basalt flows which are believed to be the most widespread in the world (Baker, 1920). After deposition of Gondwana sediments, at least 13 lava flows covered the region, attaining a total maximum thickness of 1 kilometer (3,300 feet). The age of the lava flows is either upper Triassic or Jurassic.

Deposition ceased and after the lavas cooled, a period of intense erosion and structural movement occurred. The basalt while cooling became shattered by tension cracking and, therefore, was no longer a rigid rock mass. During the time interval which separates the upper Jurassic from the middle Cretaceous, faulting on a scale almost impossible to imagine must have occurred, for at this time the Gondwana of South America and the Gondwana of South Africa were supposed to have become separated. The nature and details of faulting associated with the controversial "continental drift" is poorly known but the present topography of the inner limit of the Rio Grande do Sul Coastal Plain was initiated at this time. In the northern part of the area between Tôrres and Osório (Fig. 3) the Sera Geral basalt forms an escarpment which stands some 1000 meters higher than the

adjacent flat coastal plain. Although the escarpment had retreated several kilometers prior to deposition of the coastal plain Quaternary, there has been continuing minor faulting during the Pleistocene and probably during the Recent.

After this period of intense structural activity, a relatively long period of erosion and non-deposition occurred. This erosion lasted from upper Cretaceous to middle Tertiary time. During middle Tertiary the ocean transgressed at least the southern part of the area west of the Lagôa dos Patos. This information has been derived from subsurface evidence obtained from a few scattered test wells, since the unit does not outcrop on the surface. The unnamed Tertiary formation is at least 65 meters or 213 feet thick and consists principally of sands overlapping the older crystalline rocks. The sediments include a macro and micro-invertebrate fauna indicative of deposition in shallow, warm water. Faunal evidence suggests that these sediments are probably of upper Oligocene or lower Miocene age (Fig. 8).

PLEISTOCENE

The Pleistocene of the Rio Grande do Sul Coastal Plain has never been described as a unit since it has heretofore been considered as a part of the Recent. One of the most basic reasons for this supposition was that the earlier writers (Leinz, 1948; Carvalho, 1932, etc.) considered only Recent epeirogenic uplift of the Coastal Plain rather than eustatic changes in sea level.

Isolated paleontological collections have been made from the Pleistocene sediments; mollusks, spores and pollen, and mammals have all been described. The latter are significant since they have been more thoroughly studied. Cotta (1944) reported that the most common fossil mammal finds include: Hippidium (a heavy-set South American horse), Glyptodon (a large, armadillo-like animal), Macranchenia (an ungulate), Pampatheriam (a fossil armadillo), and Haplomastodon (a South American mastodon). All of these animals are definitively Pleistocene in age and show very strong Pampean affinities.

The presence of such a mammalian fauna suggests a semi-arid cold steppe environment. This interpretation would logically lead to the following panorama during the glacial Pleistocene in Southern South America (Fig. 29):

(1) Continental glaciation was limited to the south and probably did not extend farther north than the Province of Buenos Aires, Argentina.

(2) Mountain glaciation was restricted to the Andes and extended virtually the entire length of South America.

(3) In front of the continental glaciers from the Province of Entre Rios, Argentina, throughout Uruguay, and in Southern Rio Grande do Sul loess pampas existed.

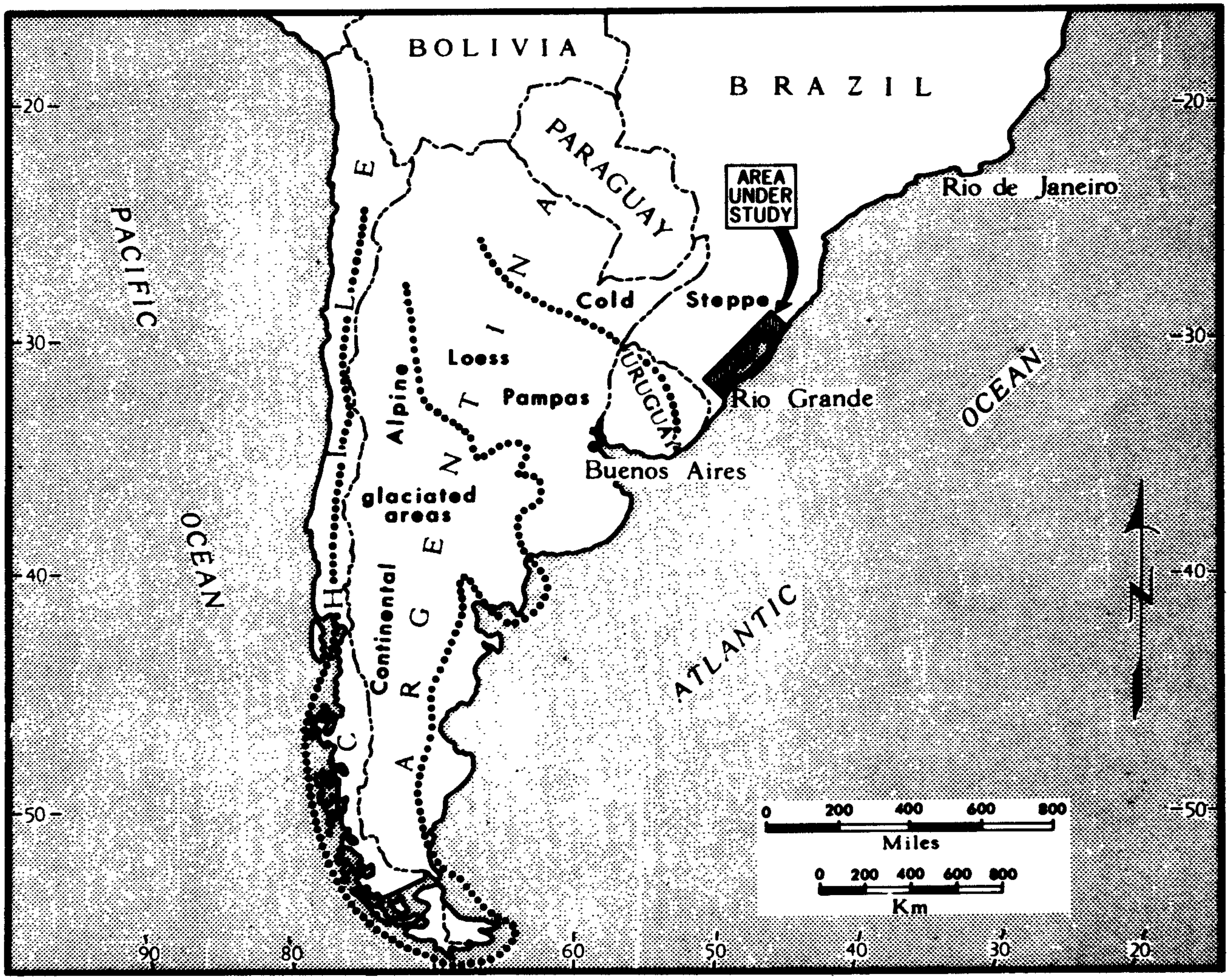


Fig. 29. Sketch map of probable paleogeography during the glacial Pleistocene.

(4) North of the loess pampas and south of the Serra Geral escarpment a cold steppe was probably present.

However, during the Pleistocene glacial stages eustatic changes in sea level resulted in comparable changes in stream base level. In Rio Grande do Sul it is not known as yet how many glacial periods and corresponding eustatic changes in sea level occurred. There is at least one known locality where stream base level was considerably lower. This is the Passo do Mendonça (Fig. 4), a gorge cut by the Camaquã River through massive rose colored, equigranular granite. The river flows against the south valley wall and is approximately 100 meters (or 328 feet) wide. The valley walls are approximately 500 meters (or 1,640 feet) apart and they stand 30 meters (98 feet) higher than the Recent flood plain. This area was thought to be an excellent area for a prospective dam site and, therefore, seven holes were drilled to depths of 40 to 58 meters (132 to 190 feet) across the valley. The granite basement was not reached. The sediments encountered were exclusively fluvial sands and gravels.

Leinz (1948) described the results of these borings and implied that block faulting had been responsible for the depth of the gravels. It seems more logical, since there is no local evidence of faulting, to assume a lower sea level with resulting stream scour to the lower base level. Subsequent rise of sea level would have caused the river to fill its own valley. The only other known situation comparable to the Passo do Mendonça is a deep hole in the Guaíba estuary off the point of Itapuã (Fig. 3) which has a depth of 40 meters (132 feet).

In the northern part of the area, between Tôrres and Osório (Fig. 3), many local terrace-like flats occur, primarily along the spurs or divides between drainage valleys cut in the basalt. It is not known whether these features are earlier Pleistocene wave-cut terraces or simply differential weathering of the various basalt flows. Further investigation is needed.

Toward the end of the last glacial period the coastal plain was probably a low-lying, semi-arid, cold steppe with podsol-type soils developed on the saprolites and arkose. By this time streams such as the Camaquã and Guaíba had cut deep valleys in response to lowered sea level. Other minor streams, such as the Arrôjo Velhaco, Arrôjo Passo Grande, etc., may have done likewise, but subsurface evidence is lacking. The orientation of these streams in a east-southeasterly direction between ridges or divides which extend into the Lagôa dos Patos suggest their entrenchment in response to a lower sea level.

As glacial conditions terminated and sea level rose, the rivers and streams of the coastal plain gradually filled their estuarian valleys with coarse sediment. The coast must have had drowned river mouths, narrow ocean beaches and perhaps incipient barrier beaches or spits. About this time, structural activity in the form of major Recent faulting took place. As a result of the faulting which uplifted and tilted large coastal blocks of sediment, two significant events occurred; the Guaíba stream system lost its outlet and the initial Lagôa dos Patos was formed in the back-slope trough of the tilted fault block. The initial barrier then was structurally formed

from uplifted, semi-consolidated Pleistocene sands. As sea level achieved stability following its rise, the structural barrier has gradually been modified by coastal processes to its present form.

RECENT

The three fundamental factors affecting geology and geomorphology of the Recent Coastal Plain of Rio Grande do Sul are structural activity, mass movement, and the eolian processes. Faulting has determined major features, but the others have been instrumental in shaping morphologic details. Had there not been post-Pleistocene faulting, it is believed that the entire area from Cidreira to São José do Norte, and possibly as far south as Santa Virória do Palmar (Fig. 2), would be submerged today.

In order to relate structural activity to present physiography a series of three block diagrams of the coastal plain has been constructed (Figs. 30, 31 and 32). It should be emphasized that these diagrams are based on field reconnaissance, that subsurface evidence is lacking, and that future work will no doubt drastically modify the third dimensional interpretation of the regional geology. Nonetheless, the diagrams clarify the relationship between faulting and morphology.

An examination of these figures illustrates how closely Recent faults parallel the present coastline. All faults are down-to-the-coast and morphology suggests rotational blocks tilted slightly landward. As loosely consolidated Pleistocene sands are exposed as fresh appearing scarps on the uplifted blocks, the faulting must have occurred late during the Recent. The scarps examined have a surface displacement of 3 to 6 meters (10 to 20 feet). A zone of lakes or swamps ordinarily lies immediately seaward of them on the downthrown block. Occasionally, at Mostardas, for example, (Fig. 31), spring lines are encountered which contribute to the fresh water lakes and swamps (Figs. 33 and 34).

Beside being responsible for the depressions and lakes on downthrown fault blocks, structural activity has played an important role in determining other features characteristic of the coastal plain morphology. The Mostardas faulting, for example, uplifted and tilted landward a crustal block. The stream complex which normally discharge through the Guaíba River into the ocean was apparently deprived of an effective outlet. These waters were seemingly deflected into the topographic low caused by the tilted fault block and forced to flow from Itapoã toward the south. Near Rio Grande, Guaíba waters, augmented by discharge from the Rio Camaquã, encountered more resistant Pleistocene sediments to the south and were able to find an outlet east into the ocean. The inefficiency of this discharge system, indicated by its low gradient and resultant need for virtually continuous dredging of the lower reaches, further attests to the Recent age of the faulting.

An additional consequence of structural activity along the Mostardas fault line was the formation of the initial barrier beach from uplifted, semi-consolidated Pleistocene sand. As sea level

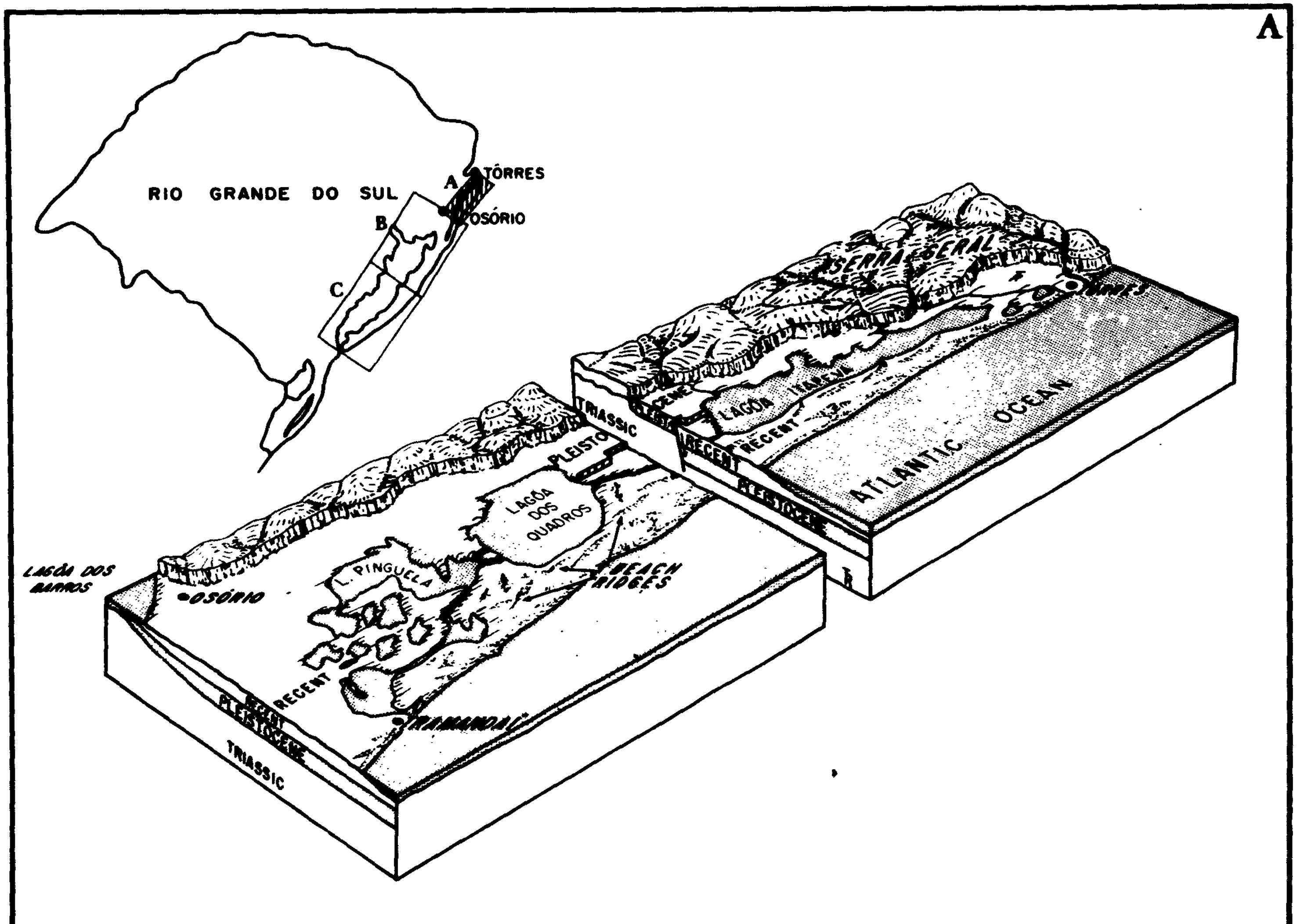


Fig. 30. Block diagram of the northern portion of the Coastal Plain of Rio Grande do Sul.

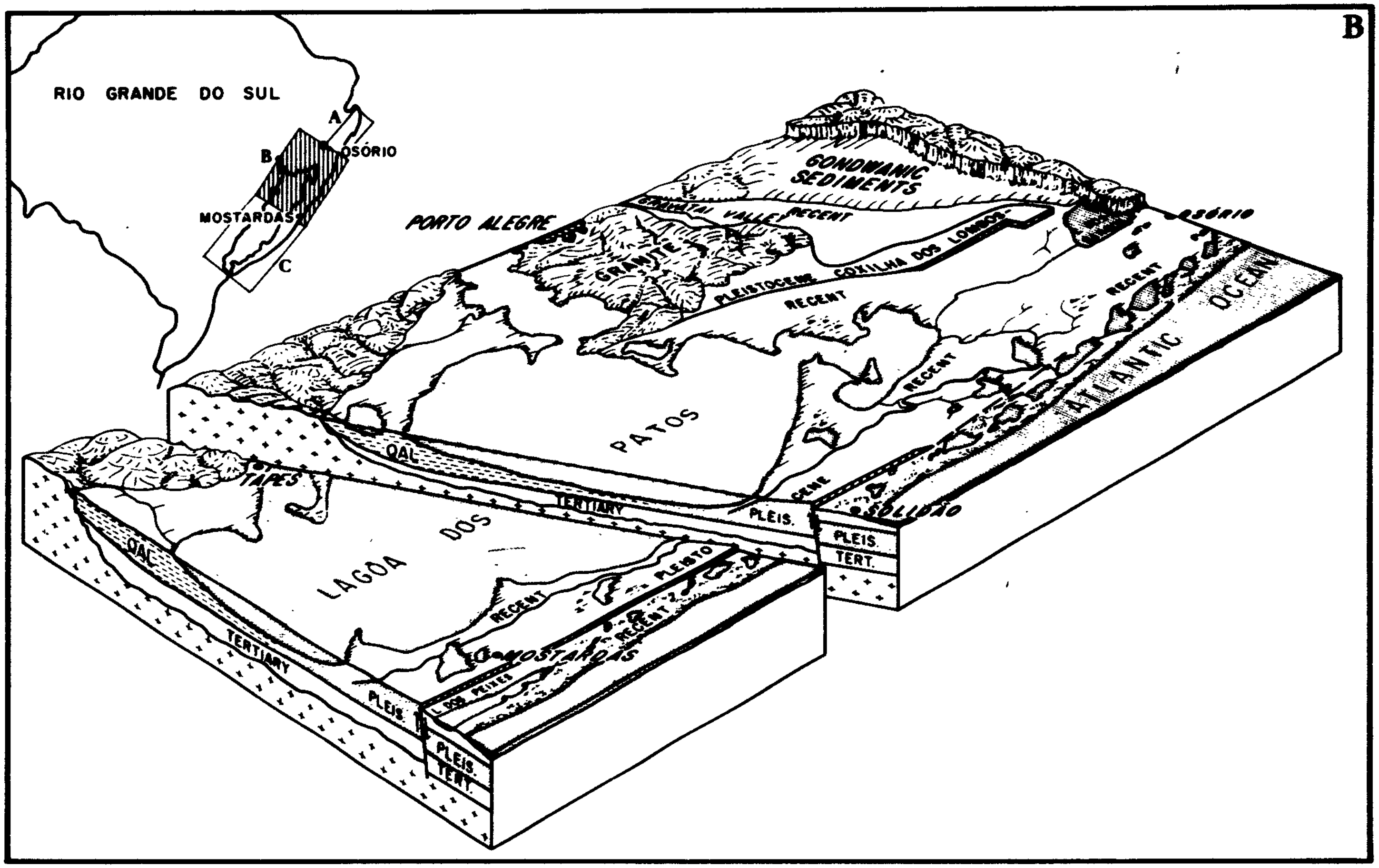


Fig. 31. Block diagram of the northern portion of the Lagôa dos Patos.

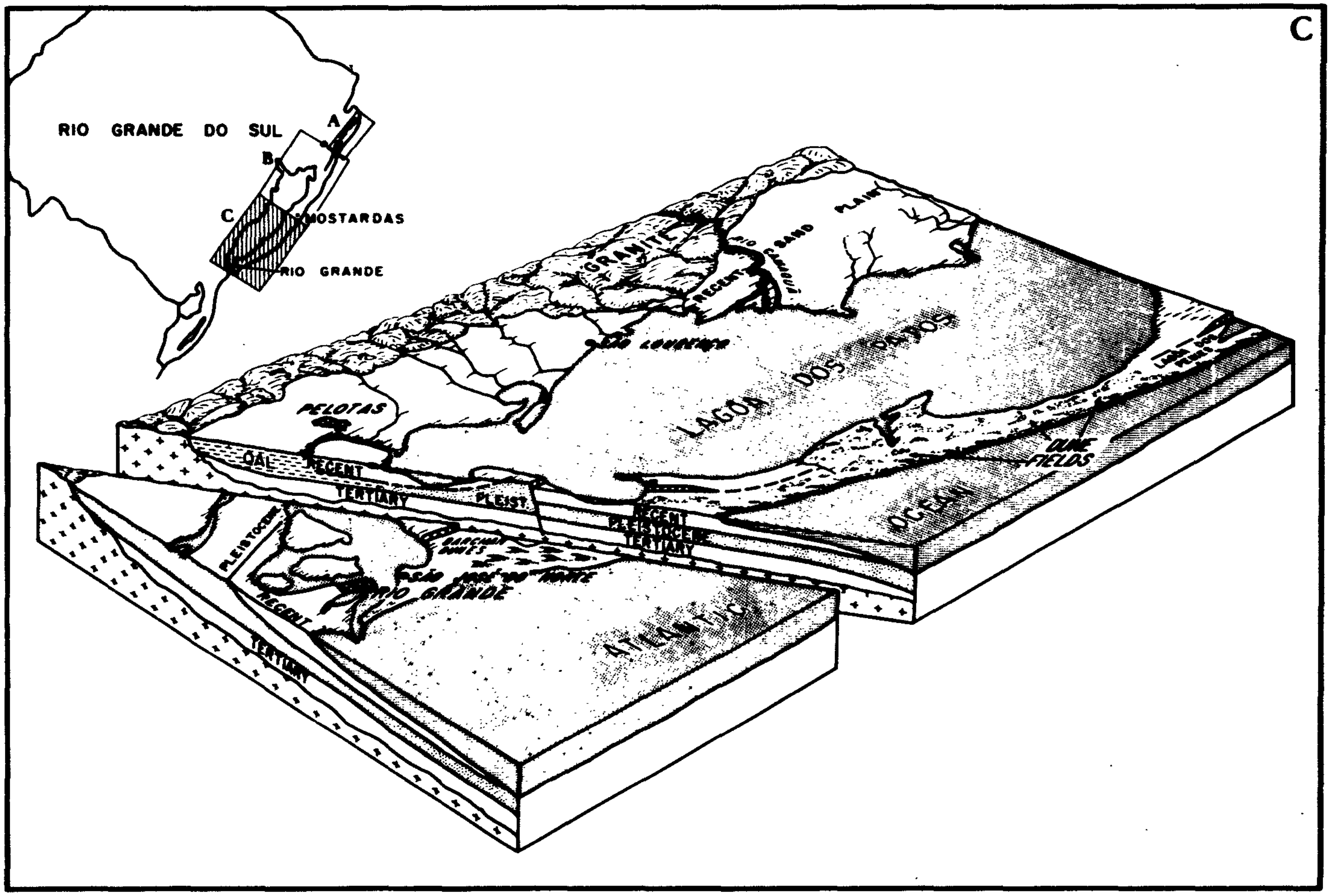


Fig. 32. Block diagram of the southern portion of the Lagôa dos Patos.

Fig. 33. Fault scarp at Mostardas (view from base of scarp).

Fig. 34. Fault scarp at Mostardas (view from top of scarp).

achieved stability following its rise, the structural barrier has gradually been widened some 3 to 5 kilometers by accretion from littoral drift.

Another important geologic process in the operation in areas where crystalline rocks outcrop is mass movement of weathered detrital sediment. This process of colluviation has been in part responsible for the down slope transportation of grus to form more than 100 meters (328 feet) of Pleistocene arkose. Although this process was perhaps more important during Pleistocene pluvial periods, it is still active today. In the area extending from Pôrto Alegre to Pelotas (Fig. 2) numerous examples of creep, catsteps, colluviation, and several minor landslides occur.

An additional important geologic factor which has greatly modified the physiography of the coastal plain is the action of the wind. This geologic process has already been discussed in connection with the development of cordiform lakes and the formation of dune fields. Wind serves as an effective erosional and transportational agent for fine sand which forms a thin blanket over most of the older rocks adjacent to the coastal plain.

Man has also acted as a geologic agent. Recently, kitchen middens or "sambaquis" have been found in the area. They usually consist of a zone of sandy black soil containing abundant potsherds and other artifacts (Fig. 35). Fifty or sixty middens have been encountered within the coastal plain, most of them containing fundamentally the same types of potsherds. The middens are most frequently encountered on Pleistocene surfaces and may or may not be covered by Recent sands. It has been generally believed that the middens of Rio Grande do Sul are only two or three hundred years old, but radiocarbon dating reported by Lamini (1960) establish that comparable middens in São Paulo and Paraná are between 1,540 and 7,525 years old. An archeological study of the coastal plain sites, including radiocarbon dating, would perhaps be significant in deciphering the later chronology of geomorphic development of coastal Rio Grande do Sul.

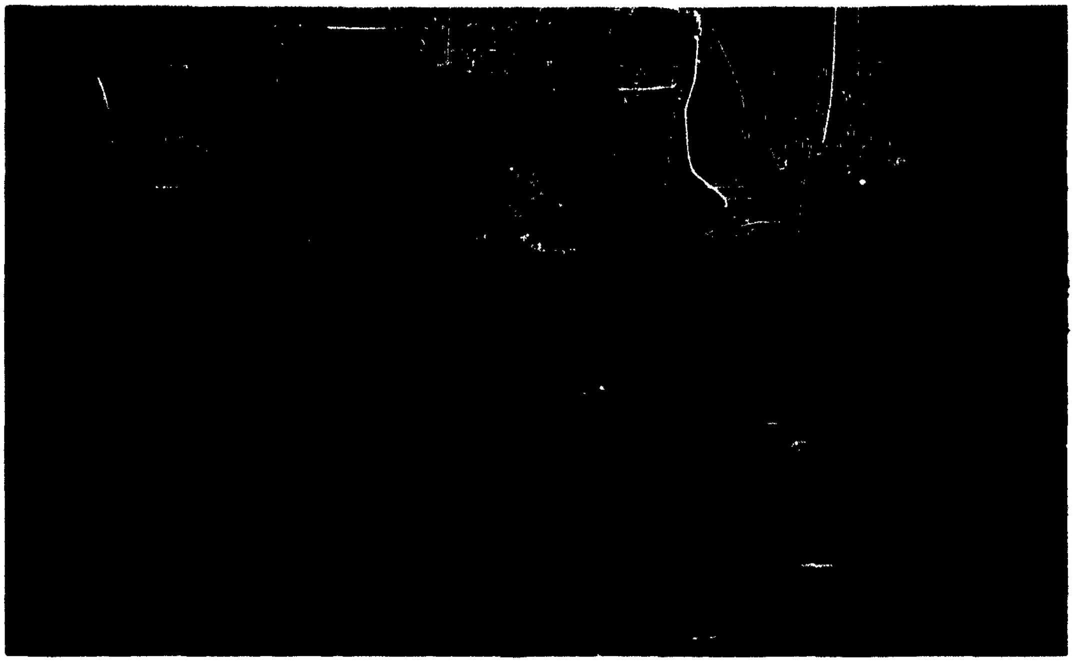


Fig. 35. View of midden or "Sambaqui" near Cassino.

Fig. 36. Sea cave near Torres.

UNSOLVED PROBLEMS

There are many fundamental unsolved problems within the area studied. First is the understanding of high level (15 meter) terraces between Tôrres and Osório. The resolution of this problem is fundamental because if it were known that these basalt platforms are really wave-cut terraces, it might indicate the amplitude of sea level fluctuations during the Pleistocene and cast some light upon the problem of epeirogenic uplift of the eastern coast of South America.

A second unsolved problem is the origin of a "sea cave" near Tôrres, (Fig. 36), which could reflect structural uplift since an earlier Pleistocene period, or perhaps correspond to a previous higher interglacial sea level. This problem is important because earlier Pleistocene morphological features have not been recognized from this part of South America.

A third problem within the area is delineation of the Pleistocene extension of the Guaíba River. This problem is important since some local geographers and geomorphologists believe that the Pleistocene drainage of the Gondwana basin included reversed flow through the present Gravataí River valley to an outlet into the ocean at Tramandaí.

These problems could be resolved in several ways. The first could be solved by regional mapping of the various levels and a detailed petrographic study of the basalt flows to see if marine erosion has cut the petrographic sequence within the rocks. The second could be resolved by extending the regional study south into Uruguay and then making correlations with the Coastal Plain of Rio Grande do Sul. The third problem would require utilization of drilling equipment and detailed sedimentological analysis of cores.

There are several other problems which are possibly even more interesting. Among them are: (1) extending the coastal morphological reconnaissance southward to the headlands in Uruguay, and (2) making a detailed stratigraphic and geomorphic study of the Recent sands of the Rio Grande do Sul Coastal Plain. The former study would be extremely important since it would be the first comprehensive geologic and physical geographic study of this large, almost completely unknown, region. It would also be interesting to see if the units and surfaces deliniated in this report are persistant to the south. The second study would be very useful as it would cast light upon one of the least understood problems - the origin of the Recent sand plain and its very subdued geomorphic features.

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